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Channel Migration in the Three-Forks Area of the Snoqualmie River

CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER

King County
Department of Natural Resources
Surface Water Management Division
River Management Section
Seattle, Washington

January 1996

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Dave Clark, River Management Section Manager

CONTRIBUTING STAFF
Susan Perkins, Geologist
Ken Zweig, Planning Support Technician

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CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER

SUMMARY

The three forks area of the upper Snoqualmie River is one of several rapidly migrating river systems in King County, Washington. Channel migration behavior between 1865 and 1993 was determined from aerial photographs and maps showing successive channel positions. Rates and types of channel migration have varied dramatically during the last century. The highest migration rates were associated with large floods such as that of 1959. Except in the North Fork, average channel migration rates were higher between 1942 and 1961 than between 1961 and 1993. Dramatic changes in channel pattern suggest that pre-1942 channel migration rates were higher still, although rates were not calculated due to the poor resolution of early maps. The post-1961 decline in migration rates was attributed to several factors, including levee and revetment construction, flood history, gravel removal, and channel pattern changes probably related to sediment load. Rapid bank erosion and channel changes continue to occur in several reaches of the study area. Differences in channel migration behavior between river reaches are attributed to floodplain slope and width, and locally to the extent of bank protection. The highest channel migration rates occur in zones of rapid sediment deposition and meander bend growth in each of the three forks.

Numerous channels cross the floodplain within the study area, many of which are wide and obviously were formed by earlier river channels. The floodplain between the Middle and South forks is a large alluvial fan whose apex is located near the Mount Si Bridge. The Middle Fork flows along the eastern boundary of the fan. Other channels that cross the fan are equally steep, or steeper, than the Middle Fork. During large floods, overbank flows could erode and enlarge existing channels between the Middle Fork and the South Fork, and potentially cause the Middle Fork to switch channels to a new course through North Bend.

The probable future limits of channel migration were defined using historic meander belt widths and bend amplitudes. Land within these limits was classified according to the relative degree of hazard from channel migration, based upon historic rates of channel migration and the presence of major bank protection structures that protect arterial roads and subdivisions.

Channel Migration in the Three Forks Area
of the Snoqualmie River

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1.0 INTRODUCTION

The upper Snoqualmie River and its three forks, in the vicinity of the cities of North Bend and Snoqualmie, is one of several rapidly-migrating river systems in King County. These rivers have a tendency to move large distances across the floodplain in a short period of time, sometimes during a single flood. Channel migration hazard areas are not shown on Federal Emergency Management Agency (FEMA) flood insurance rate maps, which only show areas subject to inundation. The FEMA maps are used by regulatory agencies, landowners, and developers to determine where development can be allowed along the rivers. King County and the cities of North Bend and Snoqualmie have all approved residential development in accordance with flood insurance maps in areas where a change of river course threatens the residences. In many cases, landowners buy the property with little awareness of the potential hazard from bank erosion. An additional complication arises because the FEMA maps are based on fixed-bed hydraulic analyses. Because of channel migration, the floodplain and floodway boundaries shown on the maps are in some cases only reliable for short periods after the maps are completed.

King County's historic approach to bank erosion problems has been to try to control rivers through extensive construction of levees and revetments. However, few new projects of this type have been built since the 1970s, due to lack of funds and the adverse effects of these projects on flooding and aquatic habitat. Projects that have been constructed more recently tend to protect specific small areas such as roads or houses. Levees and revetments are expensive to build and maintain, can aggravate flooding or erosion problems off-site, and are subject to failure due to channel migration upstream or downstream from the project. Traditional rock levees and revetments have degraded instream and riparian habitats by eliminating side channels and riparian vegetation and reducing recruitment of gravels and woody debris into rivers. Because of these problems, the King County Surface Water Management (SWM) Division recommended a policy of preventing future development in channel migration hazard areas through land-use regulation. This policy was formally adopted by the County Council as part of the King County Flood Hazard Reduction Plan in November, 1993.

In order to regulate development in hazardous zones along rapidly migrating rivers, the King County Flood Hazard Reduction Plan recommended conducting channel migration hazard mapping and studies. This report is a result of such a study for the Three Forks area of the Snoqualmie River. The study included determination of historic limits and rates of channel migration, estimation of probable future limits of channel migration, and development of maps that show channel migration hazard zones. Similar studies have already been completed for the Tolt and Raging Rivers (Shannon & Wilson, 1991) and the Green River (Perkins, 1993). Hazard maps produced by these studies have been transmitted to the King County Department of Development and Environmental Services (DDES) to use in regulating development under the Sensitive Areas Code.

The Three Forks area is shown in Figure 1. This study covers the upper Snoqualmie River mainstem from Snoqualmie Falls upstream to the confluence of the three river forks of the Snoqualmie, and each river fork upstream to a stable section of channel. Within the study area, levees and revetments (rock-armored banks) are discontinuous and subject to damage by channel migration upstream or downstream of the armored site. On the South Fork Snoqualmie River upstream from the Burlington Northern right-of-way in North Bend, channel migration has been effectively prevented for 30 years by channelization of the river between narrowly-spaced levees. Although the levee system requires frequent maintenance due to toe scour (Shannon & Wilson, 1993; King County, 1993), the channel is not expected to migrate outside the levees on this part of the South Fork. Little channel migration occurs on the North Fork upstream from Ernie's Grove or on the Middle Fork upstream from Tanner, where the channels are relatively steep and stable.

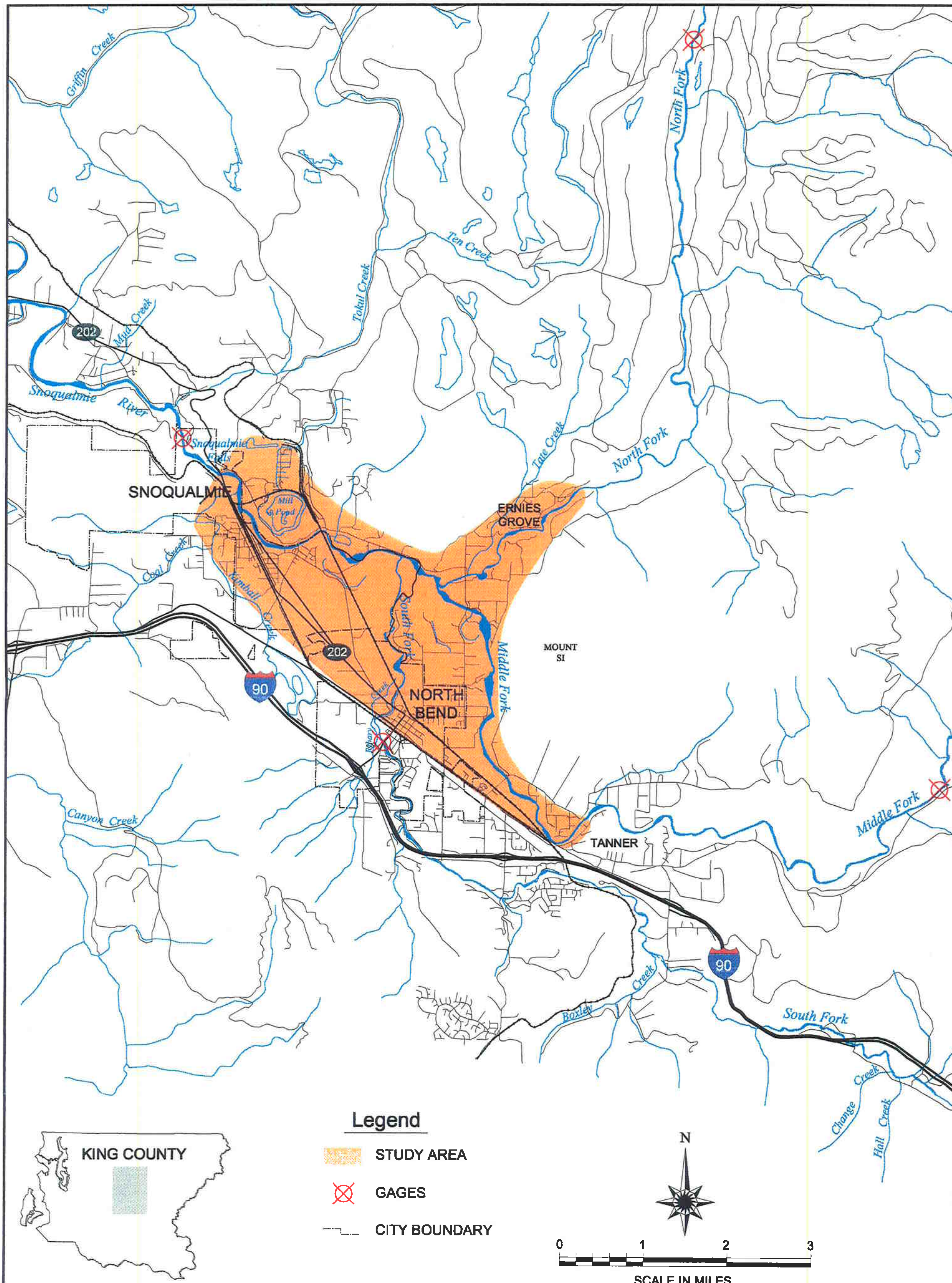


FIGURE 1

Location Map

2.0 METHODOLOGY

Field work for this study was conducted primarily in 1992 and 1994. In 1992, observations were plotted on 1989 aerial photographs and later transferred to maps. Features recorded included geologic materials, river bank height and composition, levees and revetments, vegetation type and age, presence of eroding banks, abandoned channels and other potential avulsion sites, depositional zones, and descriptions of river and floodplain morphology. Sediment sampling was conducted in 1994 to determine patterns of surface and subsurface size distribution throughout the study area.

Maps for this study were produced on the King County's Geographic Information System (GIS) using AutoCAD software and digital-line-graph base map data from the United States Geological Survey (USGS) and recent topographic mapping of the Middle Fork Snoqualmie floodplain (David C. Smith and Assoc., Inc. 1993). Historical channel positions were digitized from aerial photographs and maps whose sources, scales, and dates are shown in Table 1a. These particular maps and photographs were selected because of their availability, scale, accuracy, and timing in relation to major flood events. Table 1b shows other map and photo sources that were consulted for this study but not digitized.

Other information sources used in this study include King County inventories of revetment ages and repairs; a study of sediment transport on the South Fork and mainstem Snoqualmie Rivers (Booth et al., 1991); and river cross-sections, profiles, and topographic maps from previous and current flood studies (Harper Righellis, Inc. (HRI), 1995a, b, and c; King County, 1961; FEMA, 1995; Northwest Hydraulic Consultants, Inc. (NHC), 1994).

To construct the channel position maps (Maps 1 and 2), digitized images of the river channel at various dates were rectified to the scale of the base map by aligning common road and railway intersections. The maps show the full width of the active channel, including unvegetated gravel bars. The error incurred in representing river positions from map sources is quite minor, from 0 to 30 feet, although the original map sources themselves may contain considerable unknown errors (especially on the smaller-scale maps). The error incurred in representing river positions from aerial photographs is considerably larger due to distortion and the variable scale of the source photographs. We estimate that this error was less than 30 feet where match points were plentiful and located on both sides of the river, but as much as 50 to 100 feet where few match points existed. These larger errors occurred primarily on the Middle and North forks in the vicinity of Mt. Si.

The Three Forks area is characterized by numerous floodplain channels, many of which convey flow from the Middle to South forks and from the South Fork to the mainstem Snoqualmie. The floodplain channels shown on Map 4 were identified using topographic maps of the floodplain (see Table 1a for map sources). Floodplain channels east of the South Fork Snoqualmie were digitized from 1993 and 1995 topographic maps with a 2-foot contour interval, and therefore should be quite accurate. Floodplain channels west of the South Fork were digitized from 1961 topographic maps with a 5-foot contour interval. Although these channel locations were verified on the ground where possible, the west portion of Map 4 may be incomplete or inaccurate.

The pre-1942 channels shown on Map 1 were not used to calculate historic channel migration rates because the old surveys are of limited accuracy. Historic rates of channel migration between 1942 and 1993 were calculated from the successive river positions shown on Map 2, using procedures described in Section 4.3.1 of this report. The potential for erosion of floodplain channels was evaluated by procedures described in Section 4.4.2. The historic rates and locations of channel migration were then used in combination with other data to determine probable future limits of channel migration, as described in Section 5.1.

TABLE 1a

MAPS AND AERIAL PHOTOGRAPHS USED TO MAP HISTORICAL CHANNEL POSITIONS

Date of Survey or Flight	Type	Scale	Source
1865 1867	Maps	1:31680	Government Land Office survey 1867 S. Fork above RM 1 1865 remainder of study area
1881	Map	1:31680	King County Road Book (S. Fork above RM 1 and M. Fork above RM 46)
approx. 1910	Map	1:24000	CMSP&P Railroad
1913	Maps	1:15840	King County Road Book
1921 (1911)	Maps	1:125000	1921 USGS Sultan Quad (most of study area) 1911 Cedar Lake Quad (above RM 47)
1942	Aerial orthophotographs	1:25000	US Army Corps of Engineers (UW Map Library)
1958	Aerial photographs	1:12000	Washington Dept. of Natural Resources
1961 [1]	Topographic maps	1:2400	King County Engineering Dept. (does not cover N. Fork above RM 1)
1964	Aerial photographs	1:12000	King County Public Works (N. Fork above RM 1)
1970 [2]	Aerial photographs	1:14000	King County Public Works
1981 [2]	Aerial photographs	1:12000	Washington Dept. of Natural Resources
1992	Aerial photographs	1:12000	Walker & Assoc. for King County SWM (mainstem and N. Fork)
1993 [1]	Topographic maps	1:2400	David C. Smith & Assoc., for King County SWM (M. and S. Forks)
1995[1]	Topographic maps	1:2400	David C. Smith & Assoc., for King County SWM (N. Fork floodplain channels)

[1] This source was used to map the floodplain channels shown on Map 4 and the river channels of unknown age shown on Map 1.

[2] The digitized channel was not printed on Map 2 for the sake of clarity.

TABLE 1b

OTHER MAP AND PHOTO SOURCES CONSULTED FOR THIS STUDY

Date of Survey or Flight	Type	Scale	Source
1914	Map	1:10000	King County Engineers Office Weeks Road Survey No. 1155
1922	Map	1:4800	King County Public Works Blake Road Survey No. 1807 (upper Middle Fork near Tanner)
1973	Aerial orthophotographs	1:12000	US Army Corps of Engineers
1985	Aerial photographs	1:12000	Washington Dept. of Natural Resources
1989	Aerial photographs	1:14000	King County SWM
1993	Aerial photographs	1:7800	David C. Smith & Assoc., for King County SWM (M. and S. Forks)

3.0 STUDY AREA CHARACTERISTICS

The upper Snoqualmie River is located east of Seattle in the eastern part of King County, as shown in Figure 1. The three forks of the Snoqualmie River flow south and west from their headwaters in the Cascade range and meet in a broad valley between the cities of North Bend and Snoqualmie. The Middle Fork drains an area of 171 square miles, whereas the smaller North and South forks drain areas of 103 and 84 square miles, respectively. Below the confluence of the three forks, the mainstem Snoqualmie River flows northwest for several miles to Snoqualmie Falls, the downstream end of the study area. The lower Snoqualmie River, below the 268-foot-high falls, flows northwest for approximately 40 miles before joining the Skykomish River just downstream of the City of Monroe in Snohomish County.

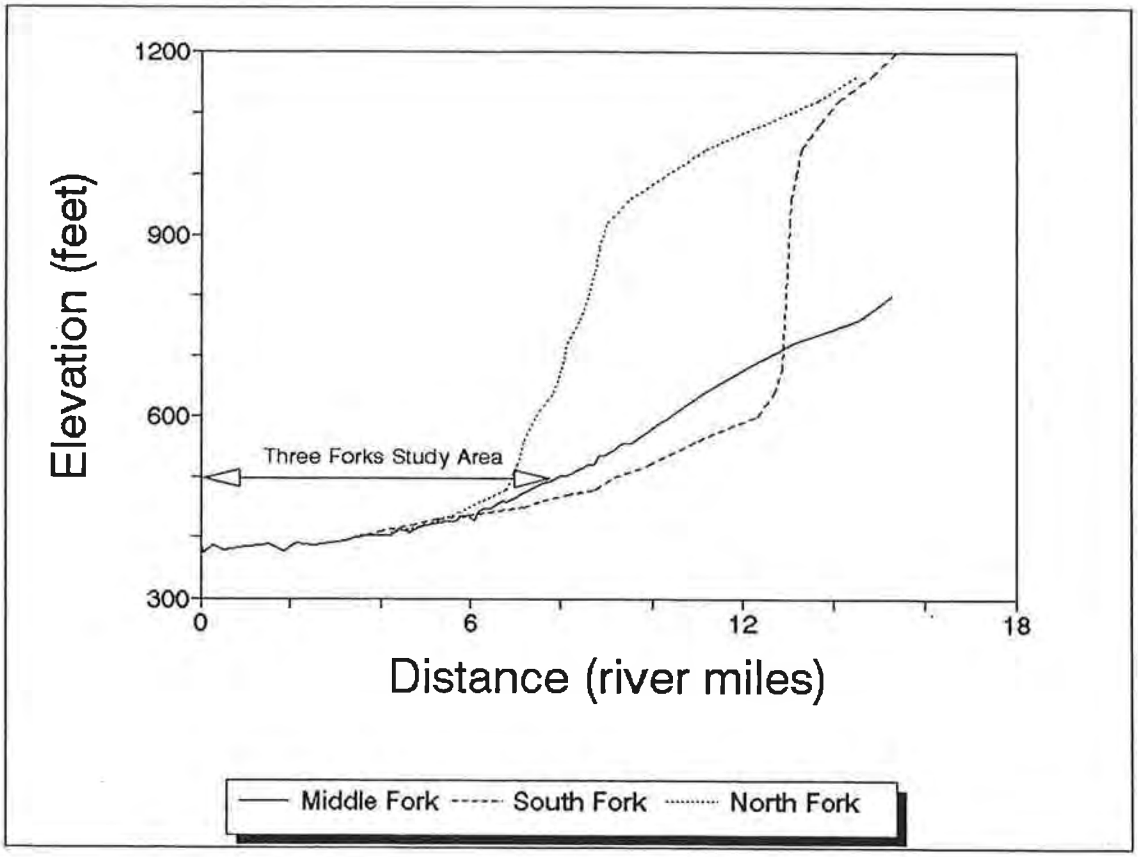
The study area consists of 12 river miles (RM) in the upper valley above the falls, and includes the mainstem Snoqualmie River as well as the lower portions of the three forks (Figure 1). The study area extends from RM 40.7 (SR 202 crossing, just upstream of Snoqualmie Falls) to the confluence of the three forks at RM 44-45, and on up the Middle Fork to just upstream of Tanner (RM 49.2); the study area also includes the lowermost 2.0 miles of the North Fork up to Ernie's Grove, and the lowermost 1.9 miles of the South Fork up to the Burlington Northern right-of-way in North Bend. (River miles are shown on the map sheets in the back of this report.) Land use in the unincorporated portions of the study area is primarily rural, but an ever-increasing number of residences are replacing the farms. In the late 1980s, King County acquired much of the riverfront property in the confluence area for Three Forks Park.

The headwaters of the three river forks are mountainous, forested terrain. Here the rivers flow through relatively confined floodplains and have steep, generally stable channels. Upon leaving the mountains, the rivers disgorge onto a broad, relatively flat, alluvial plain (Figure 2). The three river forks deposit most of their sediment load in broad gravel bars in the North Bend area. The rapid sediment deposition causes the rivers to shift laterally across the floodplain. The mainstem Snoqualmie River is somewhat more stable below the confluence of the three forks, in the vicinity of the City of Snoqualmie, in part because most of the coarser sediment has dropped out upstream (Booth et al., 1991). However, scars of abandoned channels and meander loops attest to past channel migration in the mainstem.

3.1 Bank Protection and Gravel Removal

Levees and revetments impede channel migration in many locations. Levees (raised berms designed to prevent overbank flooding, typically protected on their riverward face by rock) and revetments (rock armor placed on the bank to control erosion, not flooding) have been built in many locations along the rivers. Levees within the study area are discontinuous and offer only limited flood protection. Most are located within the regulatory floodway and restrict flood flows, redirecting and raising flood heights elsewhere. The revetments and levees have stabilized the rivers in many locations, encouraging home-building and other activities in floodplain lands once at greater risk from channel migration and flooding. However, the bank protection is not fail-safe. Many of the river facilities built by King County have required repeated maintenance and repairs since their construction in the 1960s, most recently following severe damage during two floods in 1990.

Figure 2
River Profiles



Map 3 shows locations of known existing levees and revetments and their approximate dates of construction. Most (67 percent by length) of these facilities were constructed in the 1960s (Figure 3) with funds raised by King County bond issues. The older facilities, for which King County has no records, are shown where known from aerial photographs or anecdotal evidence. Revetments and levees are present along at least one river bank for 45 percent of the channel length in the study area. However, the facilities are unevenly distributed within the study area. As Figure 4 shows, revetments and levees line at least one bank in most of the North Fork study area but almost none of the banks in the South Fork study area. In addition to bank protection, seven bridges have impeded channel migration within the study area. Most of the bridges constrict the channel and have associated bank protection measures.

The largest gravel-removal operation in the Three Forks system occurred on the South Fork Snoqualmie River between 1964 and 1966. Gravel was removed from the river channel and used to construct levees in the City of North Bend, upstream from the study area. An estimated 62,600 cubic yards of gravel were removed from the river between North Bend Boulevard and Interstate 90 (I-90) upstream (Shannon & Wilson, 1993), a volume equivalent to about 15 years of bedload sediment flux (Booth et al., 1991). In the same river segment, 1,200 cubic yards of gravel have been removed annually since 1956 from a single bar, and almost 27,000 cubic yards were removed in 1991 (Shannon & Wilson, 1993). A similar but much smaller excavation was completed in the same reach in 1994. No volume estimates are available for the gravel removed for levee construction downstream from North Bend Boulevard.

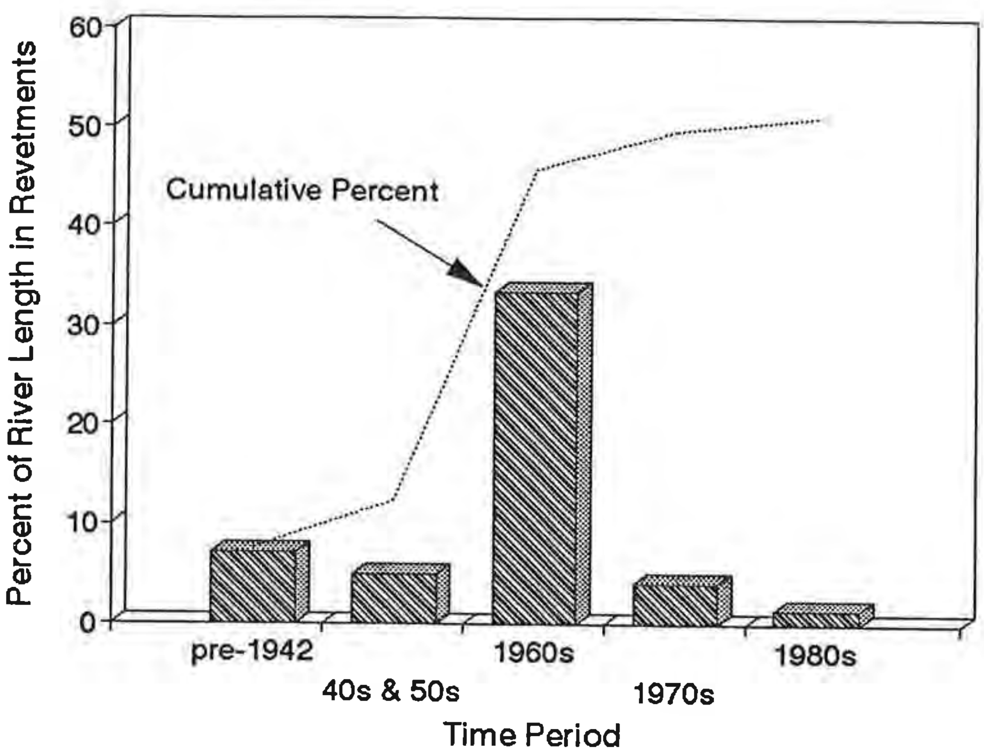
Gravel removal elsewhere in the Three Forks area has been more limited in scope. Gravel was removed from a bar just downstream of the North Fork-Middle Fork confluence for three years in the early 1960s (Irene Scott, personal communication, 12-13-94). Gravel was sporadically removed from individual bars on the North Fork (near Vallcuda levee) and near the Middle-North Fork confluence in the 1960s and 1970s (Jerry Creek, personal communication, King County SWM, 3-27-95). Other instances of dredging or gravel bar removal probably have occurred within the study area, particularly in conjunction with levee construction during the 1960s, but there are no records to confirm this.

3.2 Flooding in the Three Forks Area

The Snoqualmie River system is unique among major King County rivers in that its flows are not regulated by reservoirs. There are two small hydroelectric projects on the South Fork Snoqualmie upstream of the study area that impound very small volumes of water and have a negligible effect on water and sediment discharge. Puget Power operates a larger hydroelectric project atop Snoqualmie Falls. This project affects the low-flow river elevations throughout reaches M and C, as well as in the downstream ends of reaches NF1, MF1 and SF1. The dam's hydraulic control becomes less important as flows rise.

During moderate to large floods, flows from the three river forks combine to inundate the Snoqualmie-North Bend area. Flood waters leave the Middle Fork channel in the vicinity of Mount Si (between RM 46 and 48) and flow northwest across the floodplain toward the South Fork. Overflows from the

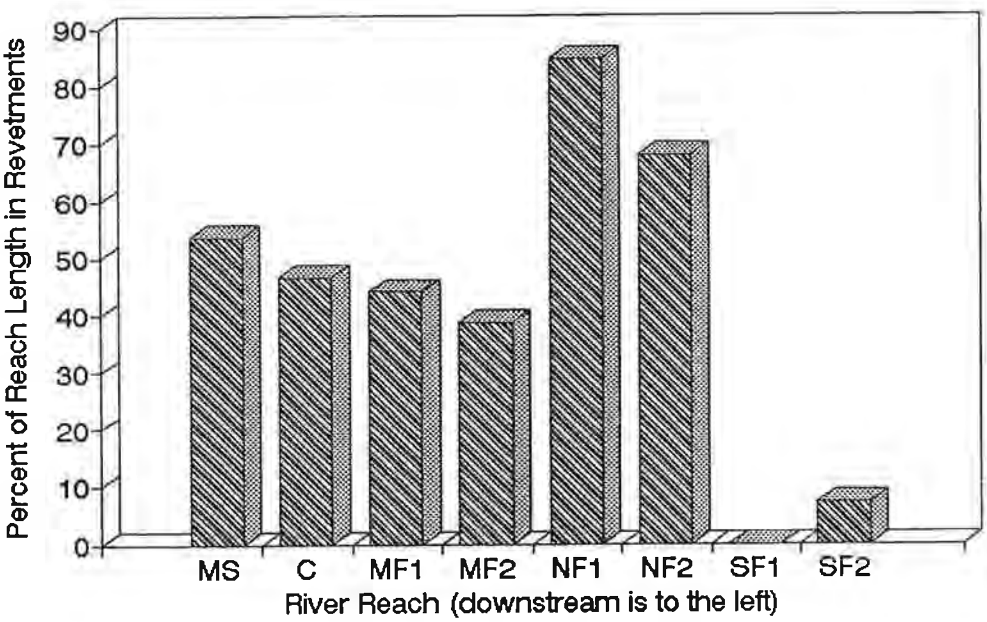
Figure 3
Revetment Construction History



Note: The figure shows the percentage of river length with a revetment or levee along one or both banks.

Figure 4

Revetment Extent by Reach



Note: Figure shows percentage of reach length with a revetment or levee along one or both banks in 1993. See Map 3 for revetment locations and river reaches.

South Fork travel north and west to the mainstem Snoqualmie via Kimball Creek or Meadowbrook Slough. Much of the overbank discharge is concentrated in a system of floodplain channels in which flows can be deep and fast. Some of these flood channels are scars of former river channels that were left behind as the river migrated across the valley floor.

Figures 5 through 8 show historic peak annual floods for the mainstem Snoqualmie River and each of the three forks (refer to Figure 1 for gage locations). These floods typically occur in the months of November through February and are associated with warm maritime frontal storm systems. Prolonged high flows also occur during spring snowmelt, but these discharges are rarely great enough to overtop the river banks. The relative magnitude of floods reflects differences in basin area and elevation, with the mainstem and Middle Fork experiencing far greater peak discharges than the two smaller forks (Table 2).

To fill data gaps in the Middle Fork, mainstem, and South Fork flow records, peak flows were estimated by correlation with nearby gages. Peak flows for the missing period of record between 1933 and 1959 on the Middle Fork were estimated through correlation with flows at the North Fork gage. The correlation was good ($r = 0.863$), reflecting the proximity of the two basins. The mainstem Snoqualmie River record from the gage near Snoqualmie was extended backward 30 years by correlation with the gage near Carnation, 17 river miles downstream. The correlation was good ($r = 0.945$).

The South Fork Snoqualmie River near North Bend has been gaged intermittently since water year (WY) 1909, with large gaps in the record in the 1940s, 1950s, and 1980s. Peak flows for the missing years were estimated by correlation with data from nearby gages to complete the record (Shannon & Wilson, 1993). Although the actual gaged flows at North Bend suggest a sudden increase in peak flow magnitude starting as late as WY 1960 (the 1959 floods), the flood peaks estimated by correlation suggest that the increase in peak flows may have started as early as WY 1942. It should be noted, though, that high flow years on these two forks do not always coincide and the correlation between the North and South Fork gages is only "fair" ($r = 0.64$; Shannon & Wilson, 1993). A case in point is WY 1932, when the largest flood of record occurred on the North Fork but the South Fork flood peak was unremarkable (Figures 7 and 8). In contrast, the 1959 flood was a more regional event that produced large floods on all three forks.

The timing of the most severe floods varies between basins. The largest flood of record occurred in 1959 (WY 1960) on the Middle and South Forks, in 1932 on the North Fork, and in 1990 (WY 1991) on the mainstem Snoqualmie. The largest floods on the North Fork occurred in the 1930 to 1960 period, while in contrast, the largest floods on the South Fork occurred in the 1950 to 1990 period. Based on the estimated flows, flood size and frequency have been more uniform on the mainstem Snoqualmie and the Middle Fork. All four gages recorded relatively low floods during the 1960s and early 1970s. This period of quiescence extended until the mid-1980s on the North Fork.

Table 2

Flood Magnitude and Frequency

Return Interval (years)	Discharge at Mouth of River (cfs)			
	Snoqualmie mainstem	Middle Fork Snoqualmie	North Fork Snoqualmie	South Fork Snoqualmie
2	28,000			
10	50,000	28,000	18,600	9,200
25	62,000			
50	71,000	38,300	24,600	13,300
100	80,000	43,800	27,200	15,100
500	103,000	55,800	32,800	19,800

Figure 5

Snoqualmie River near Snoqualmie

Peak Annual Discharges

Drainage area 375 sq. mi.

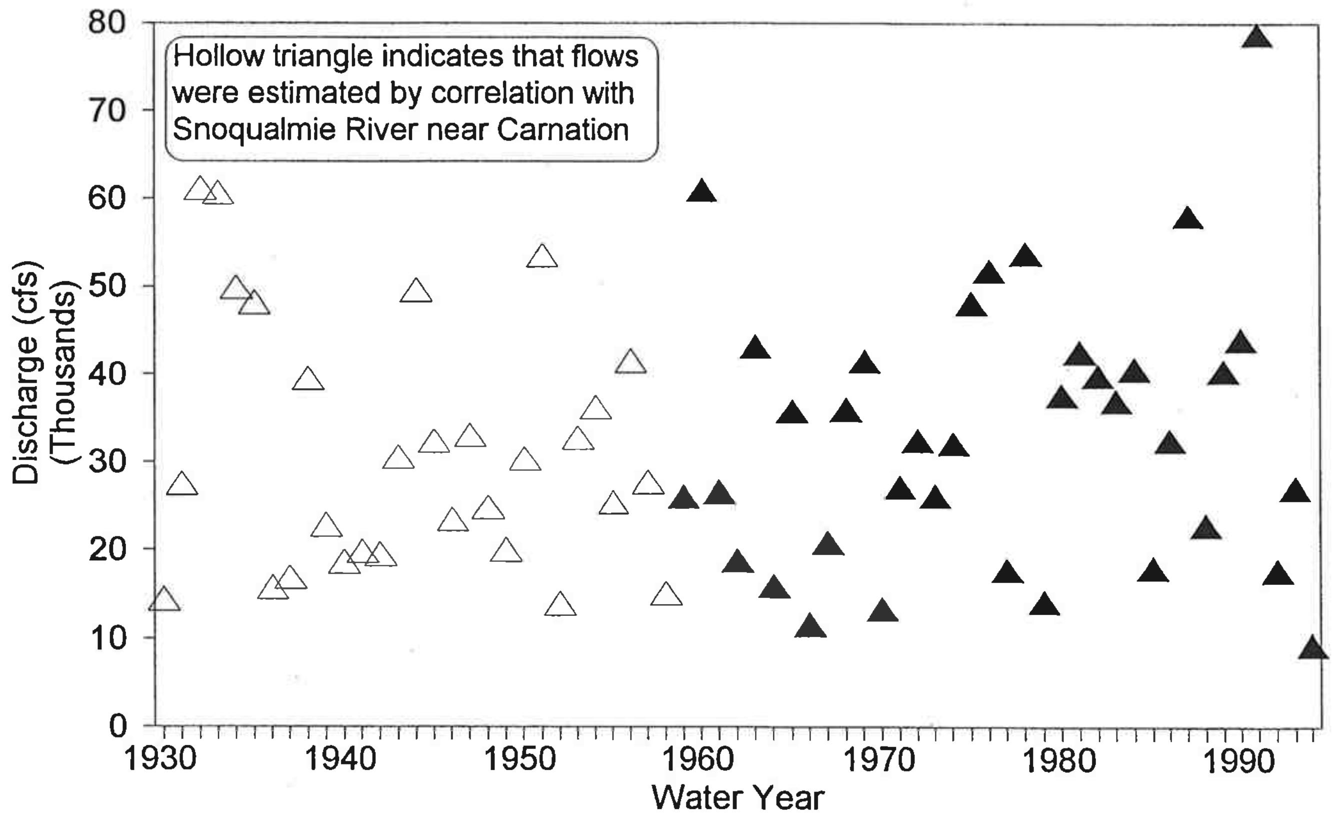
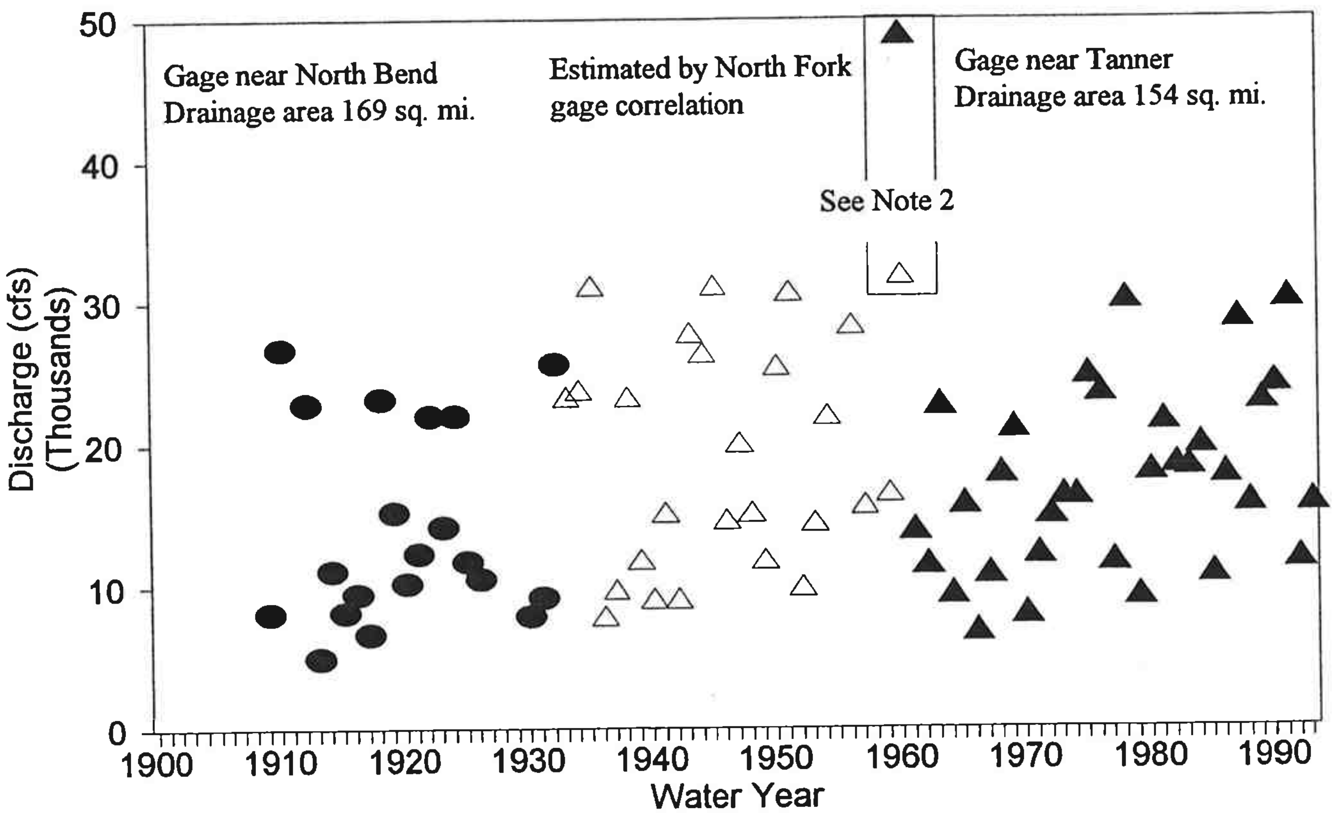


Figure 6

Middle Fork Snoqualmie River

Peak Annual Discharges



Notes:

1) r = 0.863 for correlation between North Fork and Middle Fork gages.

2) WY 1960 discharge was estimated by slope-area method at a site 6 miles downstream from the Tanner gage. As shown on this figure, the same flood estimated by correlation with the North Fork gage was much smaller.

Figure 7

North Fork Snoqualmie River

Peak Annual Discharges

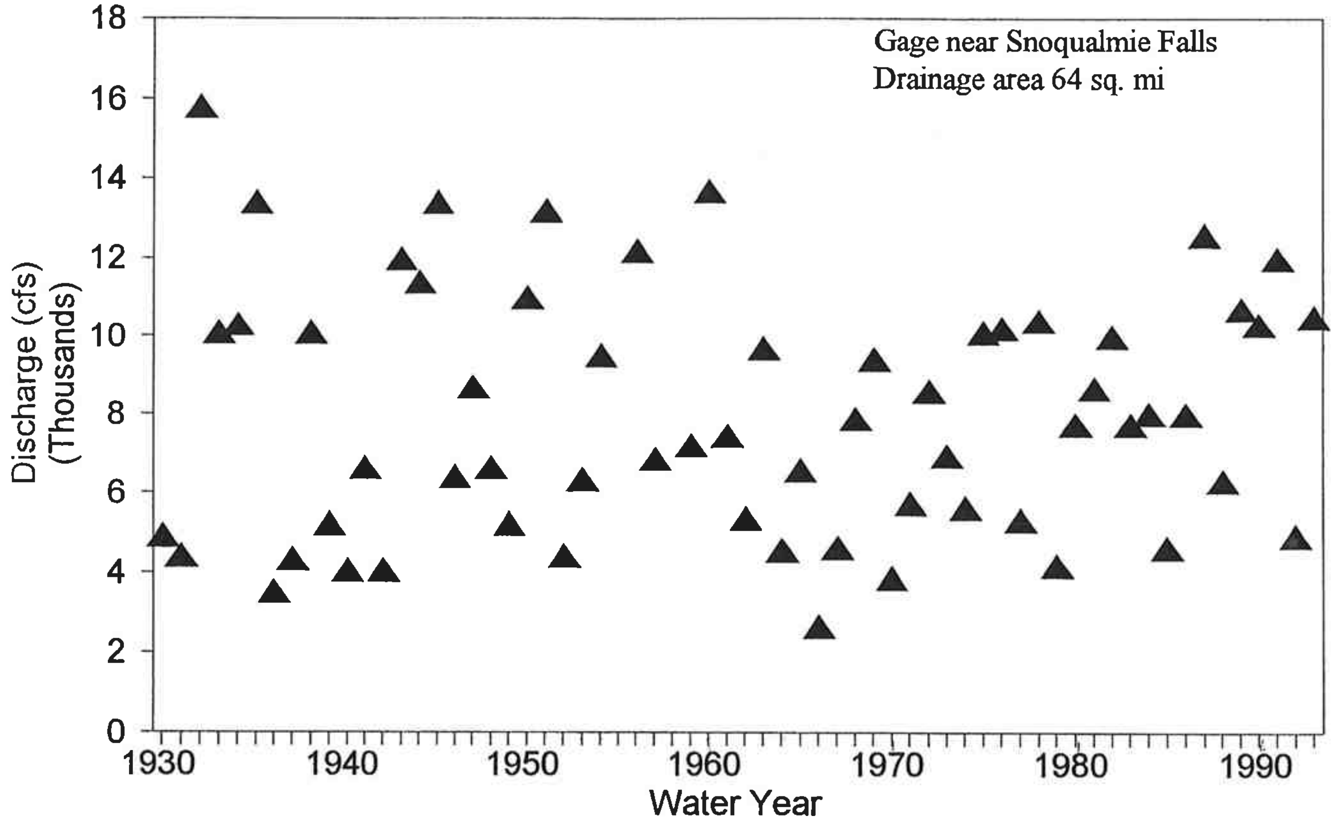
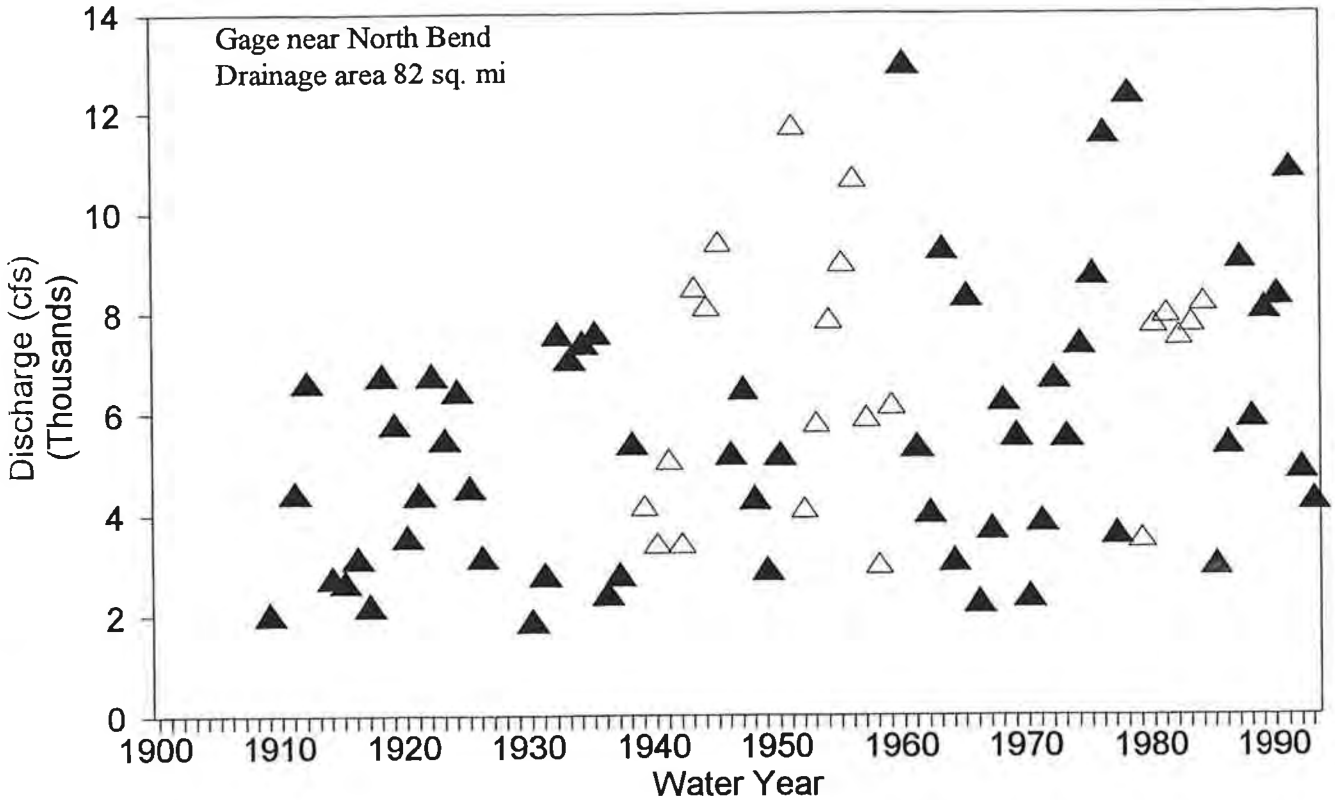


Figure 8

South Fork Snoqualmie River

Peak Annual Discharges



▲ Flows gaged on South Fork near North Bend, except WY 1960 estimated by slope-area method at gage site.

△ Flows estimated by correlation with nearby gages on South Fork at Garcia (1980s) or North Fork (1940s and 1950s). Source: Shannon & Wilson, 1993.

3.3 Geology and Sediment Characteristics

3.3.1 Geology

The Three Forks area of the Snoqualmie River is located in an embayment in the Cascade Range mountain front. Here the forks of the Snoqualmie River emerge from the mountains and deposit their coarse sediment load on the broad, gently-sloping valley floor between Snoqualmie Falls and North Bend (Booth et al., 1991). The rivers flow primarily through alluvial deposits of unconsolidated gravel, sand, and silt that have been laid down and reworked by the rivers. In places, the rivers abut older geologic materials at the edge of the valley floor. These include glacial deposits as well as the bedrock escarpment of Mount Si. Figure 9 shows the geologic units that form the valley walls adjacent to the river in the study area, as mapped by Frizzell et al. (1984) and Booth (1990). These valley-wall bank materials are less erodible than alluvium and limit lateral migration of the rivers.

Sediment deposited by rivers and streams is termed **alluvium**. In the study area, alluvium is composed of poorly-consolidated gravel, sand, and silt. The alluvium is underlain by up to hundreds of feet of Quaternary glacial deposits, which in turn overlie bedrock. Virtually the entire floor of the upper Snoqualmie Valley is composed of alluvium. Most of the alluvium is part of the active floodplain and is flooded episodically by the river. In places on the upper forks of the Snoqualmie, the river has cut down through its alluvial deposits and left its former floodplain(s) behind as one or more terraces. Although river terraces are not subject to flooding except in extreme events, they remain subject to lateral erosion by the river.

Recessional outwash forms the valley wall on the north side of the study area, and also forms the valley floor of the North Fork upstream from Ernie's Grove. No outwash deposits are presently exposed in the river banks within the study area. Although the Snoqualmie River flows close to the north valley wall, it is separated from it by a road and does not presently impinge on it. The recessional outwash was laid down by meltwater streams during retreat of the ice sheet at the end of the Vashon Stade of the Fraser Glaciation, approximately 14,000 years ago. The outwash consists of stratified sand and gravel with layers of silty sand to silty clay. The deposits on the north valley wall are predominantly sandy, while the North Fork deposits are predominantly gravelly. Because these deposits were not compacted by glacial ice, they tend to be loose and prone to erosion if exposed to running water.

The Middle Fork Snoqualmie flows next to the **bedrock** wall of Mount Si for much of its length. Bedrock also forms the east wall of the North Fork Snoqualmie valley, although the North Fork does not impinge on the valley wall within the study area. The bedrock is a pre-Tertiary melange, a pervasively-sheared matrix of mostly argillite containing small to mountain-sized inclusions of a variety of lithologies (Frizzell et al., 1984). Along the Middle Fork, steeply-sloping Mount Si is formed by a very large inclusion of hard, erosion-resistant metagabbro and metavolcanic rocks. On the north and northwest sides of Mount Si, bedrock is mantled in places by colluvial and alluvial fan deposits of cobbles and boulders (Booth, 1990).

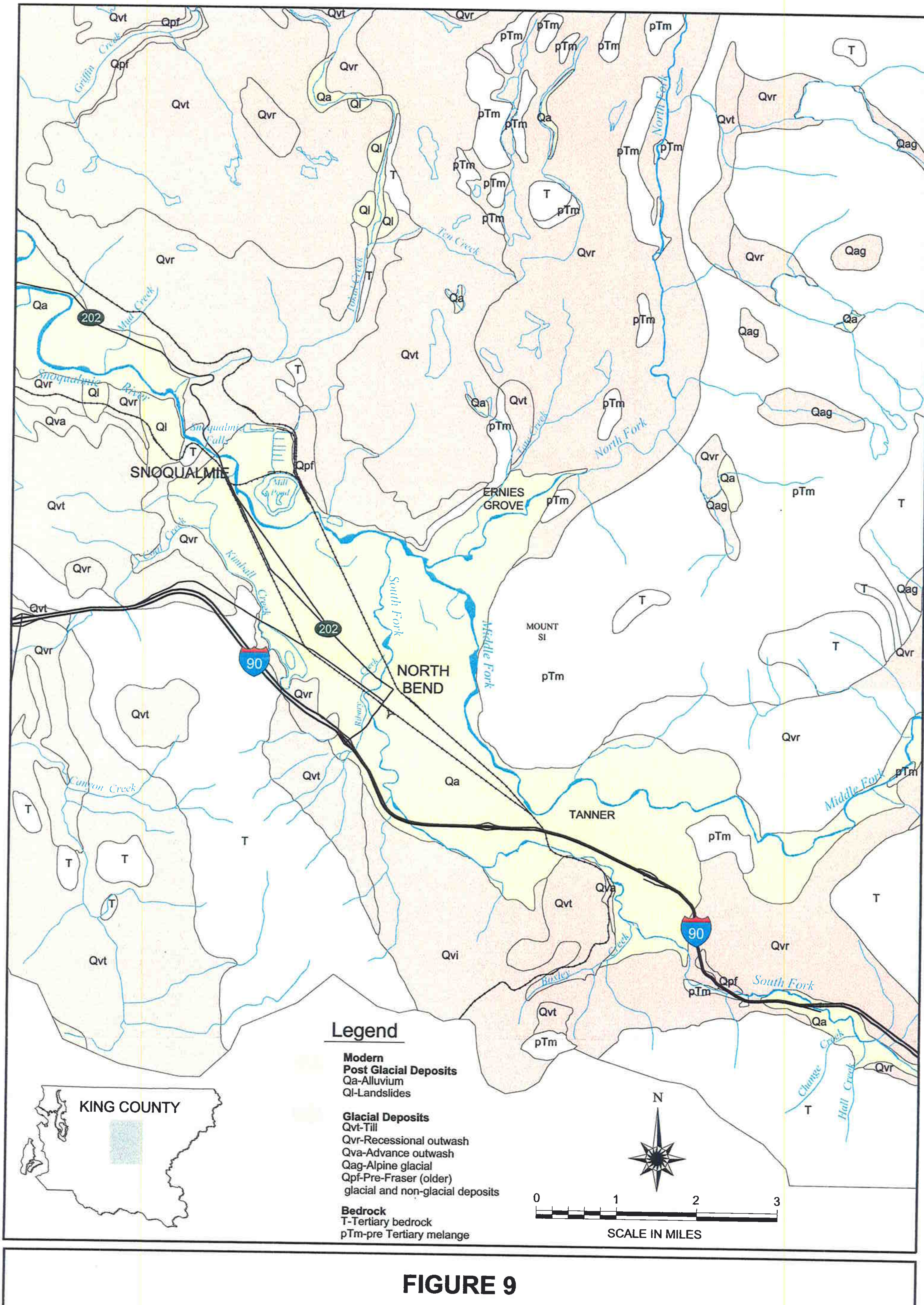


FIGURE 9

Generalized Geologic Map of the Three Forks Area

Sources: USGS Open-File Maps OF-82-747 and OF-84-693

3.3.2 Sediment Size and Bank Composition

As each of the three forks descends into the Snoqualmie Valley, the slope of the valley floor decreases and the floodplain widens. These changes cause sediment-transport capacity to decline in a downstream direction, which in turn results in downstream fining of sediment. This section describes the downstream changes in sediment size that occur within the study area. The relationships between declining transport capacity, sediment deposition, and channel migration rates are discussed in Section 4.5.1.1. Sediment size also directly affects bank resistance to erosion, as discussed in Section 4.5.1.2.

River-bank Composition

Alluvium in the study area is generally composed of two layers: coarse channel deposits overlain by finer overbank deposits. Channel deposits are predominantly gravel and sand that move downstream as bedload and are deposited in bars and the channel bottom. As the river shifts laterally away from a bar, fine sediment settles out of suspension on the former bar, building it up to the level of the adjacent floodplain. A typical composite river bank thus consists of a coarse lower bank covered by a layer of finer overbank sediment.

In the Middle and North forks, the channel deposits that comprise the lower banks are primarily gravel and cobbles. In the South Fork, the channel deposits are primarily fine gravel. The overbank deposits are typically loose, non-cohesive, fine sands and silts whose thickness ranges from a few inches to over five feet, although overbank deposits between two and four feet thick are most common. Since overbank deposits build up over time, they are generally thickest and most extensive in areas which have not been occupied by a river channel for many centuries. In many cases, these areas occur on higher ground near the sides of the valley. However, some actively eroding banks on the river have very thick overbank deposits, proving that the presence of thick overbank deposits does not guarantee that the channel will not migrate to a particular area. Banks on the North and South Forks typically range from 5 to 7 feet in height, and on the Middle Fork from 7 to 10 feet.

On the mainstem Snoqualmie, downstream of the North-Middle Fork confluence, channel deposits are much finer and typically less than three feet thick, and they nearly disappear by RM 44 at the South Fork confluence. This reflects the mainstem river's inability to transport gravel downstream of the confluence. Sediment transport modeling by Booth et al. (1991) indicates that 90 to 95 percent of the South Fork's bedload is deposited in gravel bars before reaching the mainstem. The lack of gravel deposits in the mainstem suggests that a similar proportion of bedload is deposited in the Middle and North Fork above the confluence. Banks along the mainstem are higher, reflecting the greater size of the river, and are typically composed of 8 to 10 feet of silt and fine sand overbank deposits underlain by 0-2 feet of sandy pebble-gravel channel deposits.

Downstream Changes in Sediment Size

The size distribution of bedload sediment carried by a river is most easily measured on gravel bars. Because the channel deposits that form the toes of river banks originated as gravel bars, measurements of gravel bar sediment also provide data on lower-bank sediment size.

The size distributions of surface and subsurface sediment on gravel bars of the South Fork and mainstem Snoqualmie were measured in 1989 and 1990 by Booth et al. (1991). Similar measurements on the Middle and North forks were performed for this study in 1994. In both studies, sampling was performed in a consistent location on the upstream half of each point bar, to allow comparison from bar to bar and minimize the confounding effects of spatial variability within each gravel bar. Bar surface sediment was sampled using the point-count method (Wolman, 1954). Subsurface samples were wet-sieved on site using the method described by Booth et al. (1991). No subsurface samples were obtained upstream from North Fork RM 1.0 and Middle Fork RM 45.1, due to the large calibre of the sediment. Sediment size data from this and the previous study are tabulated in Table 3.

Within each of the three forks as well as the mainstem Snoqualmie, sediment size generally decreases downstream. The decline in sediment size is illustrated by Figure 10, which shows the median diameter (D_{50})[1] of bar-surface sediment. This decline is most rapid and systematic in the Middle and North Forks, where in two miles surface D_{50} decreases from approximately 100 mm cobbles to 36 mm gravel at the forks. Sediment deposits are finer in the South Fork study reaches (surface D_{50} approximately 20 mm). On all three forks, extensive gravel bars occur in the zones of rapidly-declining sediment size. In the mainstem Snoqualmie River, downstream of the South Fork, bars are relatively few and small. Sediment size continues to decline to a surface D_{50} of 10 mm (fine pebbles) near Snoqualmie Falls. The subsurface sediment samples, which approximately represent the size of bedload being transported by the river, also show a downstream decline in sediment size (Table 3).

[1] Median diameter (D_{50}) is the size for which 50 percent of sediment particles are smaller.

TABLE 3
Sediment Size Data

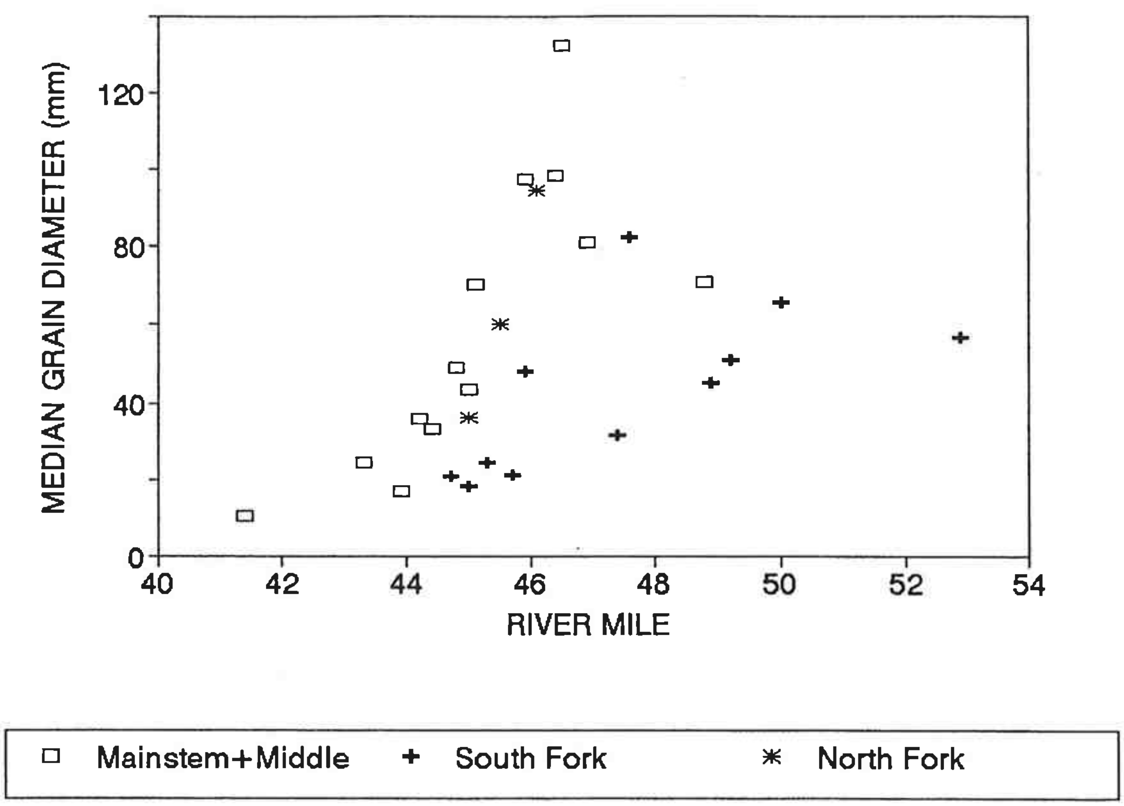
SAMPLE LOCATION	RIVER MILE *	SAMPLE NUMBER (Booth, 1991)**	SUBSURFACE diameter (mm)			SURFACE diameter (mm)		
			16%	50%	84%	16%	50%	84%
Mainstem above falls	41.4	53	0.9	5	15	5	10	20
Mainstem	43.3	54				11	25	44
Mainstem @ South Fk.	43.9	55				5	17	29
Middle Fork	44.2		2.4	28	85	14	36	72
Middle Fork	44.8		6.4	25	70	18	49	88
Middle Fork @ North Fk.	45.0		6.0	46	77	14	43	95
Middle Fork	45.1		7.3	52	97	32	70	111
Middle Fork	45.9					41	97	173
Middle Fork	46.4					30	98	222
Middle Fork	46.5					29	133	286
Middle Fork	46.9					24	81	284
Middle Fork at Tanner	48.8					11	71	230
North Fork	0.5		2.1	29	90	12	36	96
North Fork	1.0		3.9	56	129	23	60	122
North Fork	1.6					12	95	185
South Fork	0.7	56				6	21	43
South Fork	1.0	57				6	19	46
South Fork	1.3	58	1.3	8	34	6	25	44
South Fork	1.7	59				7	21	50
South Fork	1.9	60	5.7	25	60	21	48	70
South Fork in North Bend	3.4	61				12	32	71
South Fork	3.6	62	6.8	39	108	29	82	136
South Fork	4.9	63				21	45	99
South Fork	5.2	64				23	51	127
South Fork	6.0					12	66	193
South Fork nr. Edgewick	8.9					10	57	185

NOTES:

* River Miles used for this study are consistent with those used by the US Army Corps of Engineers in previous studies (mainstem and Middle Fork) and with the WDF Stream Catalog (North and South Forks). To convert to river miles used by Booth et al. (1991), subtract 0.5 miles (mainstem) or add 43.5 miles (South Fork).

** Sites listed in this column were sampled in 1989 or 1990. All other sites were sampled in 1994.

Figure 10
Downstream Sediment Size Variation



4.0 CHARACTERISTICS OF CHANNEL MIGRATION IN THE STUDY AREA

Figure 11 shows all known past and present river locations in the study area, compiled from map, photographic, and morphologic evidence. This plethora of channels is shown at a larger scale on Maps 1 and 2. Map 1 shows surveyed channels from 1865 to 1922, as well as the scars of older channels of unknown age that are large enough to have been a main river channel. The channel locations shown on Map 1 are approximate due to the small scale and inaccuracy of the early surveys. However, in many locations the old surveys are corroborated by scars of former channels that are still visible on the floodplain. Map 2 shows historic changes in channel positions between 1942 and 1993. The channels shown on Map 2 were obtained from aerial photographs or maps derived from photogrammetry, and hence are considerably more accurate than Map 1. However, errors of 30 to 50 feet are possible in channel segments that were digitized from aerial photographs (primarily the 1942 and 1958 channels; see Section 2.0). Map 2 shows the active channel, defined as the low-flow channel(s) plus adjacent gravel bars that lack perennial vegetation. The active channel in many locations is considerably larger than the low-flow channel. Between-year differences in channel width on the maps in some cases are artifacts of differences in discharge between sets of aerial photographs, or of varying definitions of channel edge in the case of surveyed maps. Map 4 shows the numerous channels that cross the floodplain as single lines, regardless of width.

4.1 Morphology of the River Reaches

This section sets the stage for a discussion of channel migration rates by describing the morphology of each river reach. Morphological features such as channel gradient and floodplain width strongly influence channel migration. Conversely, historic changes in river pattern and width reflect the magnitude and type of past channel migration.

The study area was divided into eight reaches that exhibit different rates and types of channel migration and corresponding differences in river morphology. The boundaries of these reaches are shown on the Maps 1 through 4. Table 4 summarizes physical characteristics of each reach such as migration rate, gradient, channel pattern, and degree of constraint by levees and revetments.

The **Mainstem reach (MS)**, from near Snoqualmie Falls to the South Fork confluence, is a single-thread, sinuous channel. Because most of the river's coarse sediment load is deposited upstream of this reach, bars are few and small in size. The Mainstem has a much lower channel gradient than the river reaches upstream. Bridges and railway berms first stabilized portions of this reach in the 1900s and 1910s. Subsequent revetment building occurred in the 1960s. Over half the length of the reach now has an armored bank on one side. Upstream from downtown Snoqualmie, the outsides of all bends are held in place by revetments.

Low gradients, slow sediment deposition, and armored banks all combine to minimize bank erosion in the Mainstem reach. Channel migration occurs in localized areas at slow to moderate rates. The large 1959 and 1990 floods caused no major changes in channel pattern, although localized bend migration and widening occurred. Most erosion since 1942 occurred in two zones: between SR203 and RM 41.8, and near RM 43.1, about one-half mile downstream of the South Fork confluence. At the

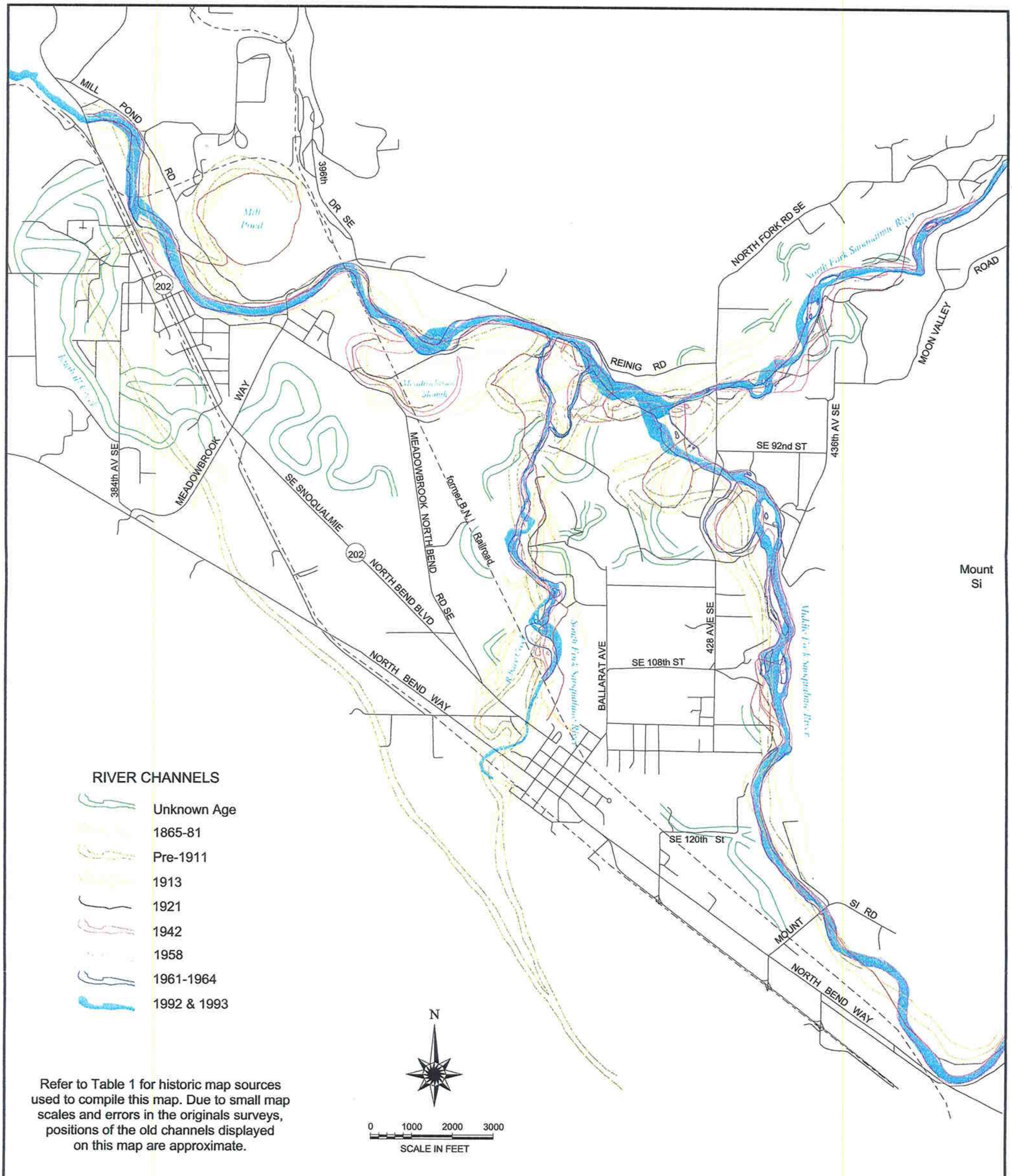


FIGURE 11

Historic Channel Locations

TABLE 4

Characteristics of Study Area River Reaches

Reach Symbol [1]	River Location	From RM: [1]	To RM: [1]	Channel Gradient (%)	Levee and Revetment Extent (%) [2]	Size and Frequency of Bars	Channel Pattern	Channel Migration [4]
MS	mainstem below S.Fk.	40.7	43.9	0.035	54	bars few and small, except near South Fork	single channel, sinuous	moderate, localized
C	confluence (S Fk to N Fk)	43.9	45.2	0.10	47	bars very large, numerous, and active	sinuous, some braiding (formerly meandering)	rapid, widespread
MF1	Middle Fk.	45.2	45.8	0.18	44	bars large, numerous, often forested	sinuous with side channels and vegetated islands	moderate, localized
MF2	Middle Fk.	46.8	49.2	0.74	39	bars small, rare except above constrictions	sinuous, single channel	slow, localized
NF1	North Fk.	0.0	1.1	0.34	84	bars large, active, and numerous	sinuous, some braiding, numerous former channels	moderate (formerly rapid)
NF2	North Fk.	1.1	2.0	0.59	68	bars localized in mid-section of reach	sinuous, narrow, single channel	slow, localized
SF1	South Fk.	0.0	1.0	0.14 [3]	0	bars small, infrequent	nearly straight, narrow, single channel	slow, localized
SF2	South Fk.	1.0	1.9	0.17	7	bars large, active, and numerous	sinuous, primarily single channel, with bend cutoffs	rapid, widespread

1 Reach boundaries and river miles are shown on the map sheets in the back of this report.
2 Length of reach with a facility on one or both banks.
3 Water surface gradient is flat during floods due to backwater from the Snoqualmie River.
4 Reflects effects of bank protection by levees and revetments.

latter site, a bend migrated downstream during the 1970s and 1980s, despite the presence of a revetment on the outside of the bend. Old surveys of the Mainstem reach show the channel in more or less the same location as today (Map 1). Meadowbrook Slough and the Mill Pond, which are oxbow lakes that occupy former river bends, had apparently already been abandoned by 1865.

The **Confluence reach (C)** extends from the South Fork confluence to slightly upstream of the North Fork confluence. It is characterized by large, numerous gravel bars and rapid channel shifting. Many of the broad bars are dissected by secondary channels, giving the reach a somewhat braided appearance. Although nearly half of the reach is revetted, the protected banks are all on the north side of the historic (post-1865) meander belt and the river remains free to migrate within that belt. However, near the downstream end of the reach, the river's course is somewhat stabilized by the Reinig Road revetment at the outside of the bend at RM 44. The meander bends in this reach have been relatively small since the 1960s. Previously the bends were much larger and the river actively occupied a greater portion of its meander belt (Map 1). Remnants of these large river bends are left today as Reid Slough and two unnamed sloughs on either side of the present course of the South Fork (Map 4). This change in channel pattern is discussed in more detail below in Section 4.6.2.

The **Middle Fork** is by far the largest of the Snoqualmie's forks. Moving up the Middle Fork from the Confluence reach, the channel continues to steepen and its morphology changes commensurately. The **downstream Middle Fork reach (MF1)** is characterized by a relatively straight main channel and long, mostly vegetated gravel bars that separate one or more side channels. The overall channel configuration has been quite stable since the 1960s despite localized areas of rapid channel migration and gravel deposition. The upstream half of reach MF1 is nearly straight where it flows along the bedrock valley wall. The **upstream Middle Fork reach (MF2)** is steeper and has a stable, single-thread channel with very coarse sediment and only a few small bars. Upstream from the Mt. Si Bridge (RM 48), the floodplain becomes narrower because the channel is incised between terraces. Both Middle Fork reaches are stabilized at the outsides of every major bend (where bank erosion would otherwise occur) by the valley wall, alluvial terraces, or revetments.

The Middle Fork has not always been as stable as Map 2 indicates. Like the Confluence reach, the Middle Fork downstream from RM 46 formerly had large meander bends (Map 1). The last of these large bends was progressively abandoned between 1921 and 1960, leaving behind an overgrown creek east of 428th Avenue SE that still serves as a flood channel. The change to a straighter channel pattern is discussed in more detail below in Section 4.6.2. The early surveys all suggest that the upstream part of reach MF1 flowed up to 700 feet farther west as recently as 1913, instead of against the valley wall as it does today. The detail of the early surveys is poor, as evidenced by the simplistic straight channels. However, the general channel location appears to be accurate because scars of former channels are clearly visible on the floodplain (Map 4). In the downstream half of reach MF2 the majority of the old maps show the river in more or less the same course as today. Channel scars on the floodplain confirm the old surveys in the upstream half of the reach, where they show the river diverging from its present course.

Like the Middle Fork, the smaller **North Fork** enters the upstream end of the study reach as a steep channel in a narrow valley confined by terraces. The deep, fast flows result in high sediment transport capacity, coarse sediment, and almost no sediment deposition or channel shifting. Upon entering the

upstream North Fork reach (NF2), gradient decreases and the valley widens slightly. This reduces sediment transport capacity and causes sediment to drop out in some areas, resulting in localized channel shifting. The reach is generally stable and mostly straight, with only local areas of sediment deposition and bank erosion. Revetments along the outsides of the right bank bends have added to the stability of this reach and reach NF1 downstream. Large boulders fallen from the slopes of Mt. Si provide natural armoring for the major left bank bend in the reach.

In the **downstream North Fork reach (NF1)**, gradient continues to decrease and flood waters spread out across the wide floodplain, causing gravel to deposit rapidly in large bars. Rapid channel migration has left behind multiple channels and given the reach a somewhat braided appearance. The Vallcuda/Burhans levee was constructed incrementally beginning sometime before 1942, straightening the river by cutting off two large meander bends and preventing channel migration on the east floodplain (Map 3). The river adjacent to the levee remained straight for nearly two decades, but the zone of active channel migration eventually shifted to the west. New meander bends developed in the 1959 flood and kept growing in amplitude well into the 1970s. In 1962, a right bank levee further confined the river to a 300-foot-wide strip at the transition between NF2 and NF1. This artificial constriction deepened the flow and shifted the zone of greatest sediment deposition downstream, perhaps contributing to rapid growth of the new bends. Westward movement of the active channel continued in the 1980s and 1990s, although in the 1990s the river became less sinuous and more braided. A large area of the floodplain between the North Fork and Tate Creek (part of which occupies a former river channel) remains available for further westward migration. Numerous floodplain channels attest to the river's presence there in the past, as suggested also by old surveys (Map 1). The North Fork's movement downstream from Tate Creek is controlled by a bridge and several bank protection facilities.

The **South Fork Snoqualmie** leaves the mountains and enters the Snoqualmie Valley nine miles upstream from its confluence with the mainstem (Figure 2). Gravel is deposited throughout most of this lower section in response to a declining gradient. Much of the gravel is deposited upstream from the study area in North Bend, where the river has been narrowly confined between levees since the 1960s. The South Fork deposits most of its remaining gravel load downstream from the levees in the **upstream South Fork reach (SF2)**, which is characterized by numerous large gravel bars and rapidly shifting channels. Sediment-transport capacity decreases rapidly downstream due to backwater flooding from the mainstem Snoqualmie, and hence the South Fork can only transport sand and fine gravel into the **downstream South Fork reach (SF1)**. Since 1942, reach SF1 has had a stable, narrow, nearly straight channel with only small, infrequent bars and slow, localized bank erosion. Northward movement of the mainstem river early in the 20th century increased the distance the South Fork had to travel to its confluence (Map 1). Perhaps to reduce this distance, sometime between 1921 and 1942 the South Fork abandoned an inherited course along a former bend of the mainstem river and took up its present, straighter course across the neck of the bend.

Channels of the South Fork formerly existed to the west of the river's present course, as indicated by old surveys and abandoned channels on the floodplain (Maps 1 and 4). Ribary Creek occupies one of these former channels. Bridges and railway embankments in North Bend apparently cut off most flow to these channels around the turn of the century and directed the South Fork through the present set of bridges, thus promoting (although not ensuring) a more easterly position of the river downstream in reach SF2.

4.2 Channel Migration Processes in the Study Area

Three primary types of channel migration occur in the study area. In order of increasing scale, these are lateral migration, chute cutoffs, and neck cutoffs (Figure 12). Lateral migration is the dominant migration process in meandering rivers with well-developed bends. Meandering behavior is best developed in low-gradient rivers with cohesive banks, or wherever a river abuts resistant material such as a valley wall or revetment that can effectively hold a bend in place. In steeper rivers with coarser sediment, cutoffs tend to destroy bends before they become large. Such rivers are relatively straight, or in extreme cases, assume a braided pattern with multiple channels. Thus, the straightness of a river can indicate the type of channel migration process at work.

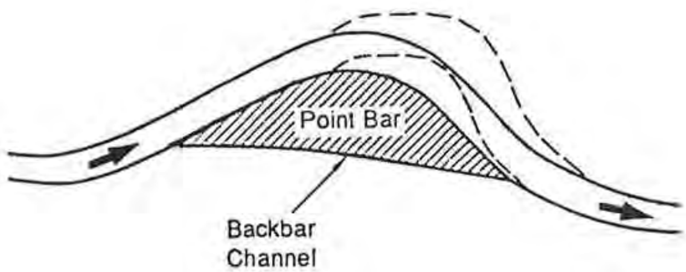
Lateral migration involves erosion of one river bank and concurrent deposition of sediment near the opposite bank (Figure 12a). This causes the channel to move laterally, generally without a net increase in width. Lateral migration typically occurs where flow converges against the outer bank near the downstream end of a meander bend. Lateral migration usually results in downstream migration of bends. New bends which form in previously straight sections of channel, and bends that are enlarging, typically grow outward as well as downstream. Lateral migration occurs in all reaches of the study area.

A **chute cutoff** occurs when a river abandons a bend and switches to a straighter, steeper path across the back of an active point bar (Figure 12b). As a meander bend develops, radius of curvature decreases and the water slope in the channel decreases upstream of the bend. This promotes sediment deposition in the channel, diversion of flow over the point bar, and a consequent cutoff. Well developed back-bar channels are common on larger gravel bars in the study area. These channels provide paths along which chute cutoffs can occur. Once a cutoff occurs, erosion of the outside of the bend slows or stops, and the area between the two channels usually becomes vegetated. Chute cutoffs often trigger rapid lateral erosion downstream by causing high-energy flows to impinge on the opposite bank at a sharp angle. Chute cutoffs are an important channel migration process in reaches C, SF2, and NF1.

The third common type of channel migration in the study area is **neck cutoff**, in which an entire meander loop is cut off at its narrowest point (Figure 12c). In many cases, an abandoned channel across the neck of the bend provides an easy location for the cutoff to occur. Neck cutoffs commonly leave a relatively undisturbed island between the old and new channels. As with chute cutoffs, neck cutoffs can trigger rapid lateral erosion downstream. Meadowbrook Slough and the Mill Pond are oxbow lakes left behind by neck cutoffs of unknown age. Neck cutoffs of large meander bends occurred in the first half of the 1900s in reaches C, SF1 and MF1. Neck cutoffs have occurred more recently in reach SF2 on two bends with amplitudes of 480 to 500 feet.

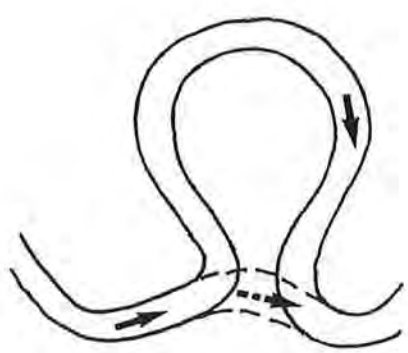
Cutoffs are a type of **avulsion**--the abrupt switching of the river to a new location. Avulsions can also occur over a greater distance than the length of a single point bar. Large-scale avulsions in many cases

Figure 12
Types of Channel Migration



a) Lateral Migration

b) Chute Cutoff



c) Neck Cutoff

Note: Dashed lines denote channel position after migration takes place.

occur where a creek or former channel provides a low path across the floodplain. Woody debris jams can sometimes trigger avulsions by diverting flow. After an avulsion takes place, flow progressively diminishes in the abandoned channel as its entrance becomes plugged with sediment and debris, although small flows may continue in the abandoned channel for decades. The new channel typically widens rapidly and progressively carries more of the flow. Islands of undisturbed land may remain between the old and new channels. Although we have no direct evidence of recent large-scale avulsions in the Three Forks study area, some of the long, split channels in reach MF1 and the river channel scars on the floodplain were probably formed by this process.

Lateral migration is an important catalyst for cutoffs and large-scale avulsions. Lateral migration can cause the river channel to intersect a potential avulsion channel, or cause a bend to develop to the point where the channel gradient is so low that water and sediment can be conveyed more efficiently directly across the bend in a cutoff. Rapid lateral migration can also lead to a cutoff by widening the channel, which spreads flow and favors development of secondary channels.

4.3 Historic Rates of Channel Migration

4.3.1 Calculation of Migration Rates

Average rates of channel migration were calculated for each reach by dividing distances between successive channel positions by the elapsed time between channel positions. Channel migration rates were calculated only for 1942 to 1993 (Map 2), since the pre-1942 channels (Map 1) were obtained from small-scale maps of questionable accuracy. To evaluate the effects of bank armoring, migration rates were calculated separately for the 1942 to 1961 and 1961 to 1993 periods. Migration rates for sections of river with armored banks were calculated separately; erosion did occur in these areas, typically when the river moved away from a levee or revetment. Migration rates were also calculated for the 1958 to 1961 period, to assess changes caused by the large 1959 flood. Comparison of the mapped 1989 and 1993 channel locations shows that channel changes during the more recent 1990 flood were not as extensive as those that occurred in 1959.

As noted in Section 2.0, the channel position maps contain errors due to uncertainty in aligning aerial photographs with the base map. Consequently, for these calculations it was assumed that mapped channel position changes that were smaller than the potential range of error were not real, unless corroborated by either 1) vegetative or morphologic evidence of a former channel on the side the river migrated away from, 2) accounts of local residents, 3) an increase in channel width, or 4) field evidence of recent bank erosion. In reach SF1 and much of MS, where erosion rates have been low, the calculated rates may therefore be lower than the true rates. On the two most stable reaches, MF2 and NF2, the amount of channel migration was within the range of potential mapping errors. Accordingly, no attempt was made to calculate average erosion rates. Instead, local bank erosion rates for these reaches were estimated from anecdotal or physical evidence of channel movement.

Average migration rates were calculated separately for each reach. Measurements were made at 200-foot intervals along the length of each reach except on the smaller South Fork Snoqualmie, where a 100-foot interval was used. At each station, the distance between successive channel edges was measured if erosion had occurred. Where the channel had shifted but remained within the boundaries of the previous channel, a value of zero was recorded.

Average rates of channel migration were calculated for armored and non-armored areas by dividing the average erosion distance for each reach by the elapsed time. For both armored and non-armored areas, average rates were calculated in two ways: for the entire reach, including non-eroding areas; and for eroding areas of the reach only. These calculations provide average migration rates. Actual rates probably varied substantially during the time intervals between successive photographs from which channel positions were measured.

4.3.2 Historic Channel Migration Rates

Average calculated historic channel migration rates for each reach are shown in Table 5. Rates for non-armored areas are shown in Table 6, and for armored areas in Table 7. These historic rates are used in Section 5 to predict future rates of channel migration. For all tables, part **a** shows average migration rates for the reach including non-eroding areas, part **b** shows average migration rates calculated for eroding areas only, and part **c** shows the proportion of each reach that actively eroded during each time period. The two columns on the left, labeled "pre-armor" and "post-armor", give migration rates before and after most of the revetments were built. The right two columns of each table give migration rates for some shorter time periods, including the 1959 flood. Table 8 gives distances eroded by the 1959 flood, the largest flood during the measurement period on most reaches. Channel migration, although locally severe, was not widespread in the 1990 flood, and hence data are not presented specifically for that flood. Table 9 gives estimated local rates of bank erosion for reaches MF2 and NF2, in which channel migration was too slow to measure long-term average rates.

Channel migration rates during the 1942 to 1993 period were highest in reaches C and SF2, moderately high in reaches NF1 and MF1, moderately low in reaches SF1 and MS, and low in reaches MF2 and NF2. In reaches with low average migration rates, erosion tended to occur only in localized areas while the majority of the banks remained stable (Table 5c).

As shown on Table 5 and Figure 13, channel migration rates have varied during the past century. The highest migration rates occur during large floods such as the 1959 event. The longer-term migration rates are lower because they include periods of little flood activity, and also because later migration tends to cancel out previous migration as channels shift back and forth across the valley floor. The highest long-term rates occurred during the pre-armor period (1942 to 1961) in all reaches but the North Fork, where migration rates were similar during both periods. The post-1961 decline in migration rates resulted both from slower erosion rates in eroding areas (Table 5b) and in some reaches because bank erosion was less widespread (Table 5c). Based on the channel positions shown on Map 1, pre-1942 migration rates on each of the forks were probably higher than the calculated post-1942 rates, which reflect the stabilizing effects of levee building, bank armoring, bridges, and railroad and road embankments.

The post-1961 decline in migration rates shown in Figure 13 coincided with extensive bank armoring on all reaches but the South Fork, which remains essentially unarmored (Section 3.1). Migration rates were computed for non-armored areas (Table 6) to remove the effects of bank armoring as much as possible. Table 6a shows that even with armored sections of river removed from the data set, the highest migration rates occurred in the 1942 to 1961 period, again with the exception of the North Fork. The post-1961 decline in non-armored migration rates resulted primarily from slower erosion rates in eroding areas (Table 6b), but in reaches MF1 and SF1 also because bank erosion was less widespread (Table 6c). In the remaining reaches, the proportion of bank length affected by erosion remained the same or increased.

Although channel migration rates were generally lower along armored sections of river, local rates of channel shifting in armored reaches have been as high as in adjoining unprotected sections of river (compare Tables 6b and 7b). Because levees and revetments in the study area are discontinuous and are typically located on just one side of a river, the river is free to erode the opposite bank or shift away from the armored bank altogether.

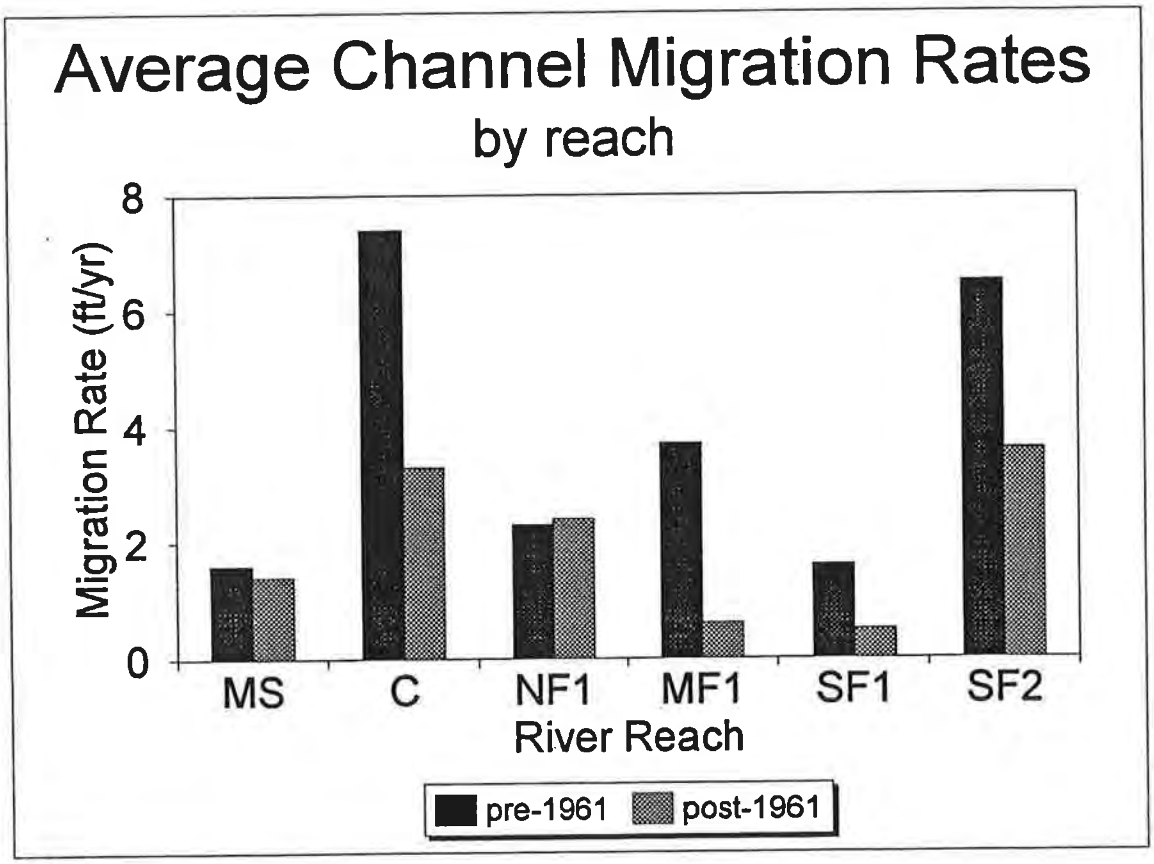
4.3.3 Comparison of Measured Channel Migration Rates with Other Studies

A sizable body of literature exists on migration rates of meandering rivers. Hooke (1980) compiled data on bank erosion rates from various rivers, primarily in the United States and Europe. The periods of measurement vary from 2 to 250 years, and most rivers in the data set have a well developed meandering pattern. Hooke's data set contains bank erosion rates of 3 to 30 feet per year for rivers with drainage areas the size of the mainstem Snoqualmie River, about 375 square miles, and 0.5 to 16 feet per year for rivers with drainage areas the size of the South and North Forks, about 100 square miles. Bank erosion rates calculated for eroding, non-armored areas of the mainstem Snoqualmie range from 3 to 11 feet per year, and for the South and North Forks from 1 to 8 feet per year (Table 6b), or generally within the range found on other rivers. Since most studies tend to focus on short reaches of rivers having significant rates of migration, and because some of the measurement periods were quite short, it is not surprising that some of Hooke's rates are higher than those obtained in this study.

Channel migration rates have been calculated for three other rapidly-migrating rivers in King County: the Tolt, Raging, and Green rivers. The Tolt drains an area similar in size to the North and South Forks, while the Green drains an area similar to the upper Snoqualmie mainstem. On the Tolt River, average rates for eroding, non-armored areas of various reaches ranged from 2 to 10 feet per year, not including avulsion channels (Shannon & Wilson, 1991). On the smaller Raging River, average rates ranged from 1 to 5 feet per year (Shannon & Wilson, 1991). On the Green River, average rates ranged from 1 to 21 feet per year (Perkins, 1993). The calculated migration rates for the Snoqualmie and its forks are similar to these other rivers, although not as extreme as their worst reaches.

In summary, the channel migration rates calculated for this study of the upper Snoqualmie River and its forks are in good agreement with rates calculated in previous studies, both for local rivers and for rivers of similar size elsewhere in the world.

Figure 13



Average Channel Migration Rates
by reach
Migration Rate (ft/yr)
8
6
4
2
0
MS
C
NF1
MF1
SF1
SF2
River Reach
pre-1961
post-1961

TABLE 5
HISTORIC CHANNEL MIGRATION RATES
BY REACH

a) Average rates for reach (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>1.6*	1.4	>0.8*	8.0
C	7.4	3.3	8.5	12.9
NF1	2.3	2.4	2.2	8.0
MF1	3.7	0.6	2.3	10.2
SF1	1.6	0.5	0.9	8.3
SF2	6.5	3.6	5.6	22.9

b) Average rates for reach, eroding areas only (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>3.5*	3.2	>4.5*	16.5
C	10.9	3.9	12.5	29.4
NF1	4.3	4.9	6.4	25.2
MF1	4.6	2.3	5.7	14.5
SF1	2.9	1.5	3.0	14.4
SF2	7.5	4.4	7.3	27.2

c) Proportion of reach length with measurable net erosion during time period (%)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>45*	43	>18*	49
C	67	84	68	44
NF1	54	50	34	32
MF1	80	23	40	70
SF1	58	36	31	58
SF2	86	82	76	84

NOTES:
-Reach MS and NF1 rates were calculated with data from 1992 instead of 1993.
-Average rates for reaches MF2 and NF2 were not calculated due to poor map resolution relative to the amount of erosion. See Table 9 for local rates for MF2 and NF2.
* indicates calculated rate is probably too low due to poor 1942 map resolution.

TABLE 6
HISTORIC CHANNEL MIGRATION RATES IN AREAS WITHOUT ARMORED BANKS

a) Average rates for reach; non-armored areas only (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>1.6*	1.8	>0.9*	8.4
C	7.6	3.9	8.0	8.6
NF1	2.8	3.7	2.4	0.0
MF1	2.6	0.5	1.1	10.1
SF1	1.6	0.5	0.9	8.3
SF2	6.5	3.9	5.6	22.9

b) Average rates for reach, eroding non-armored areas only (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>3.5*	2.6	>4.5*	16.8
C	11.2	4.2	10.9	23.8
NF1	5.5	6.5	7.0	0.0
MF1	3.5	2.3	4.1	16.0
SF1	2.9	1.5	3.0	14.4
SF2	7.5	4.8	7.3	27.2

c) Proportion of non-armored reach length with measurable net erosion during time period (%)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>45*	68	>19*	50
C	68	92	68	36
NF1	50	57	35	0
MF1	73	21	27	63
SF1	58	36	31	58
SF2	86	80	76	84

NOTES:
-Reach MS and NF1 rates were calculated with data from 1992 instead of 1993.
-Average rates for reaches MF2 and NF2 were not calculated due to poor map resolution relative to the amount of erosion. See Table 9 for local rates for MF2 and NF2.
* indicates calculated rate is probably too low due to poor 1942 map resolution.

TABLE 7
HISTORIC CHANNEL MIGRATION RATES IN AREAS WITH ARMORED BANKS

a) Average rates for reach; armored areas only (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>0.7*	1.0	>0*	3.9
C	6.0	2.8	2.1	44.4
NF1	1.7	2.0	1.4	14.7
MF1	6.9	0.5	5.9	10.3
SF1	---	---	---	---
SF2	---	1.0	---	---

b) Average rates for reach, eroding armored areas only (feet/year)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>1.8*	4.8	>0*	11.7
C	8.9	3.6	3.1	44.4
NF1	2.9	4.2	4.1	25.2
MF1	6.9	2.2	7.4	11.5
SF1	---	---	---	---
SF2	---	1.0	---	---

c) Proportion of armored reach length with measurable net erosion during time period (%)

REACH	pre-armor 1942 to 1961	post-armor 1961 to 1993	1942 to 1958	1959 flood 1958 to 1961
MS	>40*	21	>0*	33
C	67	77	67	100
NF1	58	48	33	58
MF1	100	25	80	90
SF1	---	---	---	---
SF2	---	---	---	---

NOTES:
-Reach MS and NF1 rates were calculated with data from 1992 instead of 1993.
-Average rates for reaches MF2 and NF2 were not calculated due to poor map resolution relative to the amount of erosion. See Table 9 for local rates for MF2 and NF2.
* indicates calculated rate is probably too low due to poor 1942 map resolution.
Dashed entries indicate no revetments or levees were present.

TABLE 8
SHORT-TERM BANK EROSION DISTANCES
1959 FLOOD

REACH	Maximum Distance Eroded (ft)	Average Eroded Distance in Eroding Sections of Reach (ft)
MS	130	50
C	160	88
NF1	120	76
NF2	80	----
MF1	80	44
MF2	60	----
SF1	70	43
SF2	280	82

NOTE:
The distance between the 1958 and 1961 (1964 for NF2) river banks was attributed to erosion during the 1959 flood.

TABLE 9

LOCAL RATES OF BANK EROSION
FOR THE
UPPER MIDDLE FORK AND UPPER NORTH FORK REACHES

I. Upper Middle Fork (MF2)

River Mile	Bank	Distance Eroded (ft)	Time Period	Erosion Rate (ft/yr)
47.6	Left	20 to 40	1970s to 1992	1.0 to 2.0
47.6	Right	>= 20	1950s to 1993	0.5 to 1.0
47.8	Right	approx. 20	1959 flood	20
47.8	Right	bridge washout	1959 flood	
47.9	Left	40 to 60	1959 flood	40 to 60
48.4	Left	approx. 25	1970 to 1993	1.1

Proportion of reach length with eroding bank in 1993: 21 percent

II. Upper North Fork (NF2)

River Mile	Bank	Distance Eroded (ft)	Time Period	Erosion Rate (ft/yr)
1.2	Right	20 to 80	1959 flood	20 to 80

Proportion of reach length with eroding bank in 1993: 19 percent

4.4 Potential for Erosion and Enlargement of Floodplain Channels

Numerous channels cross the floodplain within the study area, as shown on Map 4. Some of these channels contain perennial creeks or wetlands, while others are dry except during large floods. Some are wide and obviously were formed by former river channels, but many are narrower and their mode of origin is unclear.

This overbank channel network conveys large volumes of water across the floodplain during moderate to large flood events. Flows in the channels are deeper and faster than elsewhere on the floodplain. Major overbank flow paths are northwest across the sloping floodplain between the Middle Fork and the South Fork, and northwest from the South Fork to the mainstem Snoqualmie via both Meadowbrook Slough and Kimball Creek.

Many floodplain channels flow through residential communities, where they are crossed by numerous driveways and roads. Flood hazards from these channels include inundation of houses, road washouts, backwater flooding where culverts and fills reduce channel capacity, and threats to life and limb posed by deep, fast flows (King County, 1993). Floodplain channels pose additional concerns related to erosion and channel migration. In a large flood, erosion could deepen and widen channels, potentially damaging nearby houses and roads. A more extreme concern is the potential for a river to change course into one of these channels. Such wholesale switching of course (avulsion) occurred on the Tolt River in the 1980s, when a 25-foot wide creek rapidly enlarged into a 200 foot wide channel as the river abandoned its former course (Shannon & Wilson, 1991).

4.4.1 Description of Floodplain Channel Network

Map 4 shows all known floodplain channels schematically as single lines, regardless of their widths. Wide floodplain channels that are obviously abandoned river channels are also shown at their true width on Map 1. Some of these abandoned river channels correspond to channels shown on the historic maps, but most do not and are denoted as "channels of unknown age". The floodplain channels on Map 4 are subdivided into two categories: parallel and cross-floodplain.

Parallel channels are channels that flow parallel to, or have bend geometry similar to, the mainstem Snoqualmie River or one of its forks. Their planform suggests these channels could plausibly be former river channels abandoned by lateral migration. Although parallel channels were delineated on Map 4 solely on the basis of plan geometry, many of them correspond at least roughly to former channel locations delineated on Maps 1 and 2. In the Mainstem (MS) and Middle Fork(MF1, MF2) reaches, the parallel channels are almost completely contained within the documented meander belt. In the Confluence reach (C), the North Fork (NF1, NF2), and the lower part of the South Fork (SF1), parallel channels extend well beyond the meander belt documented by aerial photographs and historic maps dating back to 1865. On the North Fork, this may be because the pre-1921 maps show straight, simplistic channels that are obviously inaccurate.

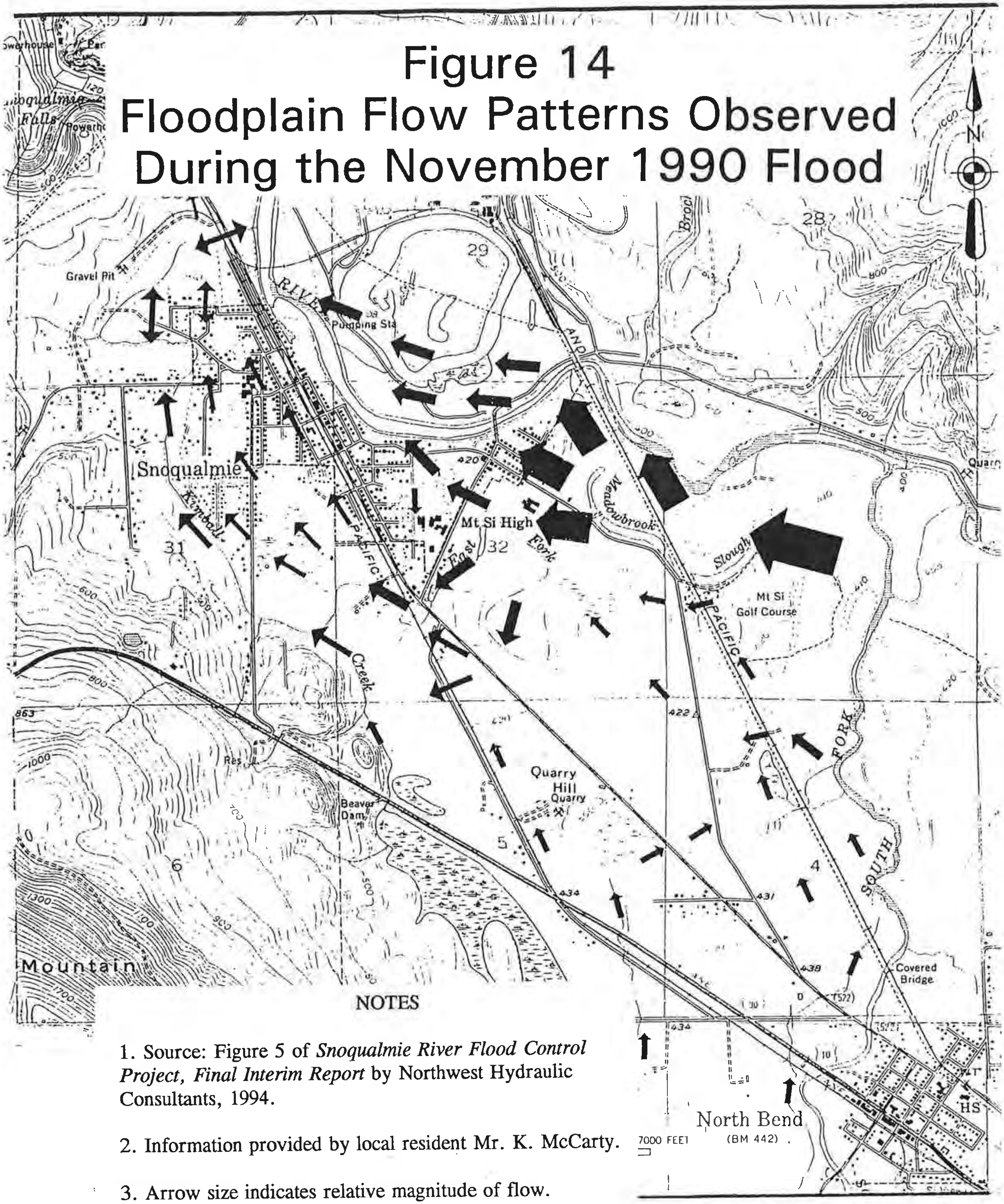
Cross-floodplain channels convey flow away from the Middle Fork or South Fork and across the floodplain. Cross-floodplain channels mostly lie outside the meander belts of the Snoqualmie and its forks. The majority of the cross-floodplain channels may have formed in the process of carrying out their present function: conveying water across the floodplain during moderate to large floods. However, several cross-floodplain channels are large enough to be former river channels (Map 1): the Kimball Creek mainstem and three adjacent channels, the east fork of Kimball Creek, the SE 120th Street channel near Middle Fork RM 47, and a short channel one quarter mile south of Reid Slough.

Many of the cross-floodplain channels west of the South Fork feed the Kimball Creek system. The Kimball Creek system contains several wide, river-sized channels that apparently once conveyed flows west from the South Fork Snoqualmie River to the mainstem Snoqualmie River near the present mouth of Kimball Creek (Map 1). Kimball Creek now conveys only local drainage except during floods, and therefore is considered a cross-floodplain channel with respect to the existing rivers.

Engineering works have reduced the potential for large flows to reach the former river channels of the Kimball Creek system. The south branch of Kimball Creek is apparently a remnant of the former Kimball's River that branched off the South Fork at North Bend, roughly at the present location of Interstate 90 (Map 1). Since the mid-1960s, levees have prevented the South Fork from overflowing in North Bend except in moderate to large floods (20-year events or greater), and have greatly reduced the amount of overbank flow when overtopping does occur. The South Fork still overtops its banks frequently downstream of the North Bend levee system in reaches SF1 and SF2. Since the early 1900s, a railroad embankment has forced most South Fork overflow northward to Meadowbrook Slough (Figure 14). Although the northerly part of East Fork Kimball Creek still receives considerable flow from the South Fork via Meadowbrook Slough, the indirect route that the railroad embankment imposes on the overbank flows reduces the gradient advantage of a direct westward South Fork-to-Kimball Creek flow route. In the 1990 flood, approximately a 60-year event on the mainstem and a 20-year event on the South Fork, localized erosion by overbank flows is known to have occurred only in two locations where flows crossed railroad tracks (McCarty, 1991; King County, 1993). Revetments on the mainstem and on Meadowbrook Slough have helped keep the mainstem Snoqualmie from intercepting Kimball Creek by migrating southward (Map 3). Due to these combined impediments, significant enlargement of the Kimball Creek channels or capture of the mainstem or South Fork Snoqualmie by Kimball Creek appears highly unlikely.

The SE 120th Street channel receives overbank flows directly from the Middle Fork and indirectly from upstream of Mount Si Bridge, via another former river channel that parallels the river (see Map 1). Overflow into these channels occurs in flood events with greater than approximately a 25-year return interval. These channels range in width from 150 to 300 feet. The SE 120th Street channel abruptly narrows upon entering the City of North Bend, where it has been filled to a top width of 30 to 50 feet and is constricted by driveways and roads with 2- to 4-foot diameter culverts. In 1990, much of the overbank flow ponded upstream of these constrictions and was forced northward through other channels. The only erosion associated with these channels in the 1990 flood (less than a 30-year event on the Middle Fork, the source of these flows) occurred where culverts overflowed and scoured road fill.

Figure 14
Floodplain Flow Patterns Observed During the November 1990 Flood



NOTES

1. Source: Figure 5 of *Snoqualmie River Flood Control Project, Final Interim Report* by Northwest Hydraulic Consultants, 1994.

2. Information provided by local resident Mr. K. McCarty.

3. Arrow size indicates relative magnitude of flow.

4.4.2 <u>Enlargement Potential of Floodplain Channels between the Middle and South Forks</u>

The floodplain between the Middle and South Forks is actually a large alluvial fan, a fan shaped land form deposited by a stream where it issues from a relatively steep, narrow valley onto a broad plain. The apex of the form is located near the Mount Si Bridge on the Middle Fork. The Middle Fork flows along the eastern boundary of the fan. Other channels cross the fan that are equally steep or steeper, as illustrated by Figure 15. Although the Middle Fork probably once was steeper than the other channels, sediment deposition near the confluence has gradually raised the river bed and reduced the channel slope. Rivers that cross alluvial fans are known to suddenly switch course to a shorter, steeper path as the former channel fills with sediment (e.g., Bloom, 1978). Based on the difference in gradients, it would seem plausible that the Middle Fork could switch channels to an equally steep, or steeper, course to the South Fork. In this section, we analyze whether overbank flows during a large flood could exert enough force to deepen and enlarge the existing floodplain channels.

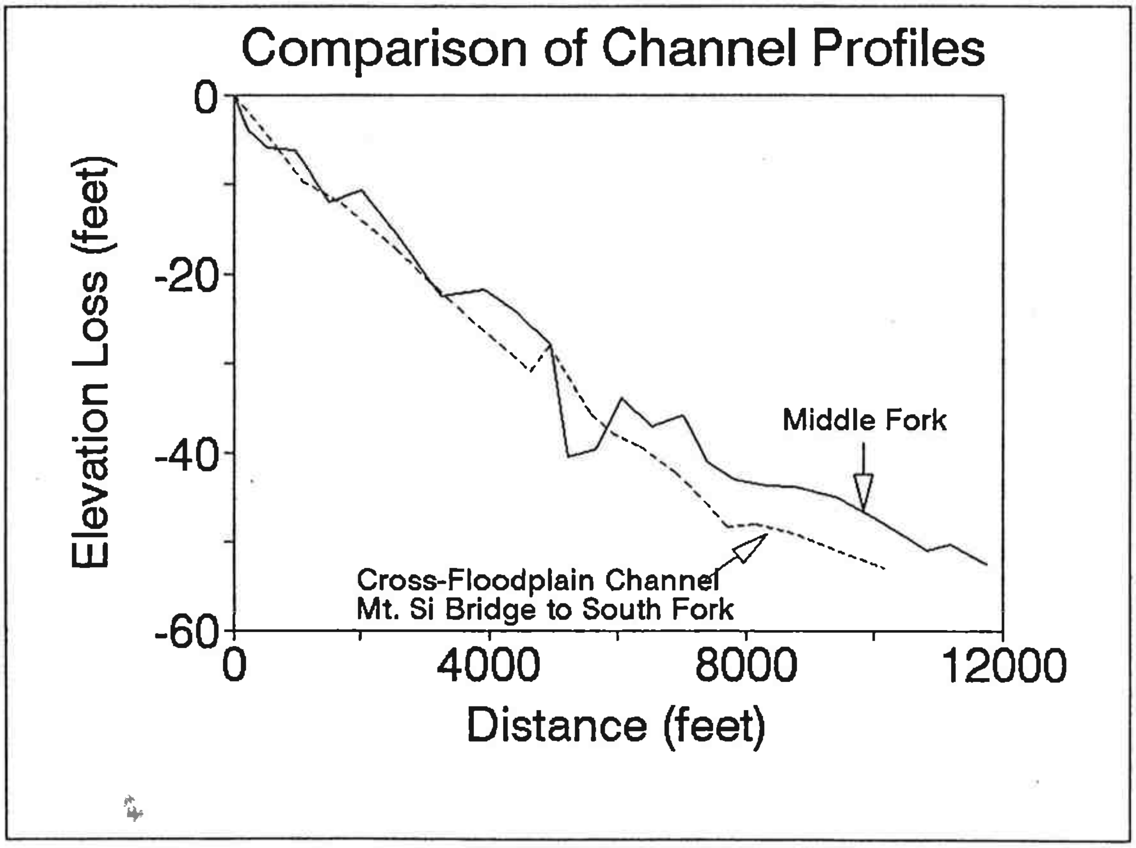
<u>Methods</u>
The enlargement potential of cross-floodplain and parallel channels between the Middle and South forks was estimated by calculating the boundary shear stress that flowing water would exert on each channel during a 100-year flood. Channel deepening and enlargement could potentially occur where boundary shear stress significantly exceeds the critical shear stress needed to erode the gravel beneath the fine sediment on the floodplain surface.

Boundary shear stress may be thought of as the erosive force that flowing water exerts on the substrate beneath it. It is defined as the product of water depth, water slope, and the unit weight of water (62.4 pounds per cubic foot). Water-surface elevations and water-surface slopes for the 100-year flood on the Middle Fork (43,800 cfs) were obtained from unpublished data from a flood study by Harper Righellis, Inc. (HRI) for King County SWM. Ground elevations in the channel bottoms were obtained from channel cross-sections surveyed for the flood study at 55 locations, and estimated from spot elevations on the flood study topographic maps at an additional 56 locations. The latter estimates are generally within two tenths of a foot of true elevation, but they tend to underestimate depth in narrow, deep channels.

Critical shear stress is the boundary shear stress at which the substrate will begin to be eroded by the water flowing across it. Critical shear stress for gravel with a median diameter (D_{50}) of 50 mm, typical for the Middle Fork upstream from RM 45, was calculated to be 1.4 pounds per square foot using the formula of Andrews, 1984. A critical shear stress of 0.7 pounds per square foot was calculated for the smaller gravel (D_{50} 25 mm) near the confluences. Critical shear stress for the fine sand and silt that form the upper several feet of the floodplain is much smaller, on the order of 0.01 pounds per square foot. At each site, boundary shear stress (T_b) was divided by critical shear stress (T_c) to determine the excess shear stress ratio (T_b/T_c). Excess shear stress ratios above 1.0 indicate that shear stress exceeds the critical value, and therefore gravel could be eroded.

Two methods were used to evaluate the enlargement potential of the channels. In the first method (Figure 16), water-surface slopes and flow depths predicted by the flood model were used to calculate shear stresses for individual channel segments. Because the HRI flood model used broad cross-sections across the floodplain to calculate flood elevations in a one-dimensional analysis, the water-surface slopes and flow depths do not reflect local conditions in the channels. In particular, flow

Figure 15



Comparison of Channel Profiles
Elevation Loss (feet)
0
-20
-40
-60
0
4000
8000
12000
Distance (feet)
Middle Fork
Cross-Floodplain Channel
Mt. Si Bridge to South Fork

depths probably are increasingly overestimated with distance from the Middle Fork. The second method (Figure 17) attempts to represent flow in the floodplain channels more accurately by using the local channel slope with a representative water depth to calculate an average shear stress for each channel. This method used the average ground slope of each floodplain channel (excluding more gently sloping channel segments immediately adjacent to the Middle Fork and South Fork) and the 100-year water depth from the flood model at the upstream end of the main section of each channel.

Results

Figures 16 and 17 show the potential for floodplain channel enlargement during a 100-year flood, as calculated by the two methods described above. Some erosion of gravel could occur wherever excess shear stress ratios exceed 1.0. Generalized transport of gravel could occur at excess shear stress ratios above 1.35 (Petit, 1994), leading to rapid channel deepening and enlargement. Erosion of fine sediment on the floodplain surface could occur in channels with excess shear stress ratios less than 1.0, but the channels could not incise into underlying gravels and therefore would be unlikely to enlarge.

The two calculation methods produce generally similar results. Enlargement potential is high along the SE 120th Street/Mount Si Bridge channel network between the Middle and South Forks. Enlargement hazards are more intermittent farther north, with some channel segments likely to enlarge and others not. On the relatively high ground east of 428th Avenue SE, most channels would not erode (Figure 16). Once overbank flows cross west over 428th Avenue SE, however, they in some cases enter erodible channels leading to the South Fork and to Reid Slough. The floodplain channels west of Reid Slough are unlikely to deepen because the water-surface gradient is nearly flat, although erosion and lateral shifting could occur within the upper sand horizon.

Scatter plots of shear-stress ratio against channel depth, channel width, water depth, and water surface slope were prepared to evaluate the effect of each variable on erodibility of individual channel segments (first method). Water depth was the dominant control of erodibility except in the Reid Slough area, where depth is almost irrelevant due to the low slope (Figure 18). Excess shear stress ratios were consistently above 1.35, the threshold for rapid enlargement, where flow depths exceeded 8 feet, and consistently below 1.35 where flow depths were less than 4 feet. Water surface slope was a poor predictor of shear-stress ratio because it varies relatively little throughout most of the area, due to the hydraulic modeling technique. However, erodible channels become more numerous to the south (upstream) as water-surface slope increases. Scatter plots of shear-stress ratio against channel depth and width showed no relationship between the size of existing channels and their enlargement potential.

Because the flood model used broad cross-sections perpendicular to 100-year flood flow of the Middle Fork, it tends to underestimate water depths near the river and overestimate water depths to the west, away from the river. The second method of calculating shear stress (Figure 17) used water depths for the upstream ends of the channels, near the Middle Fork, so water depths are if anything too low and the method may slightly underestimate erosion hazard. To assess the second method's sensitivity to water depth, shear stresses were recalculated using water depths one to two feet higher than predicted by the flood model. This raised the critical shear stress ratio to above 1.0 in some of the channels north of the SE 120th Street/Mount Si Bridge channel network, producing better agreement with results of the first method.

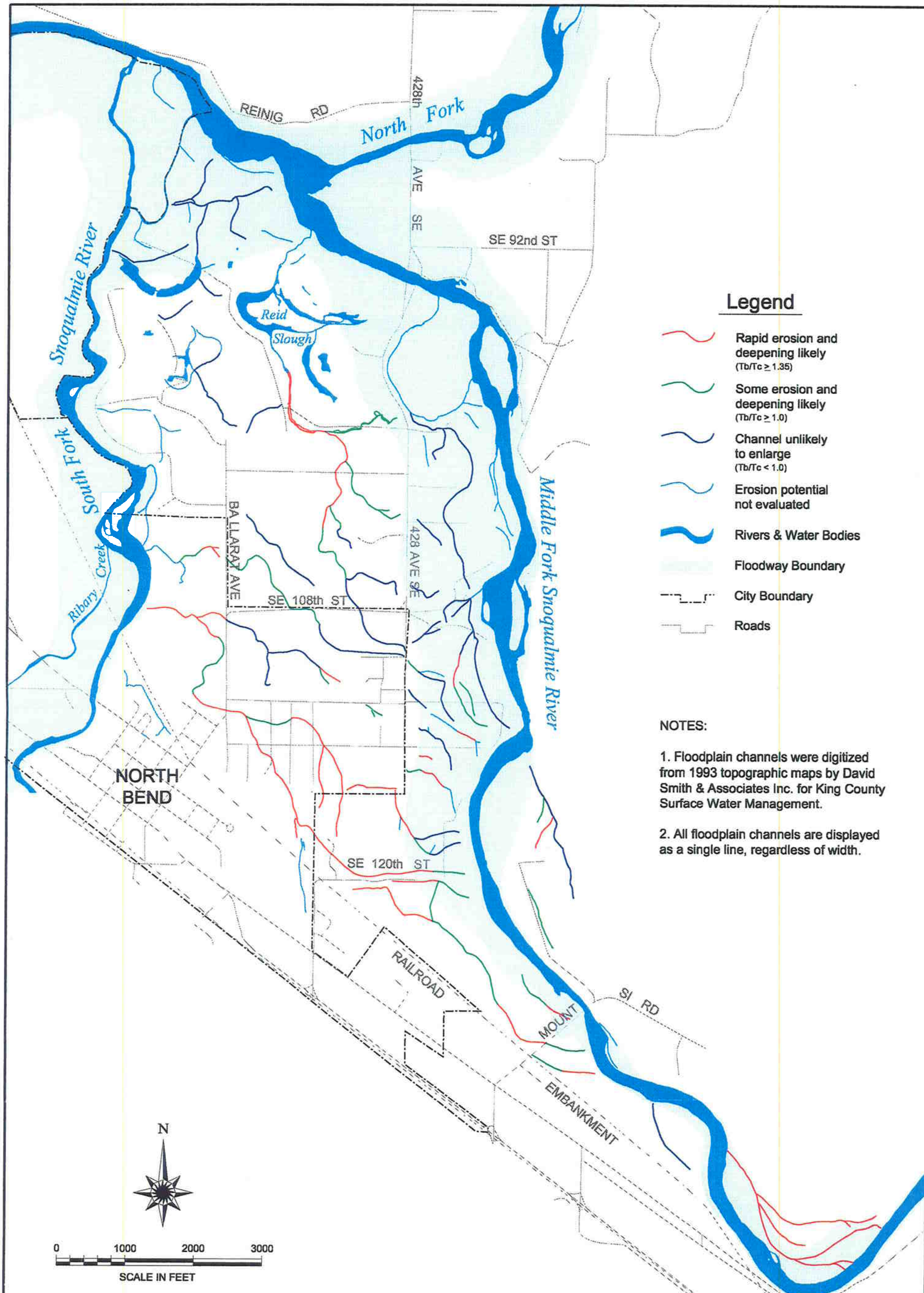


FIGURE 16

Enlargement Potential of Floodplain Channels between the Middle and South Forks
-Slopes and Depths from Flood Model-

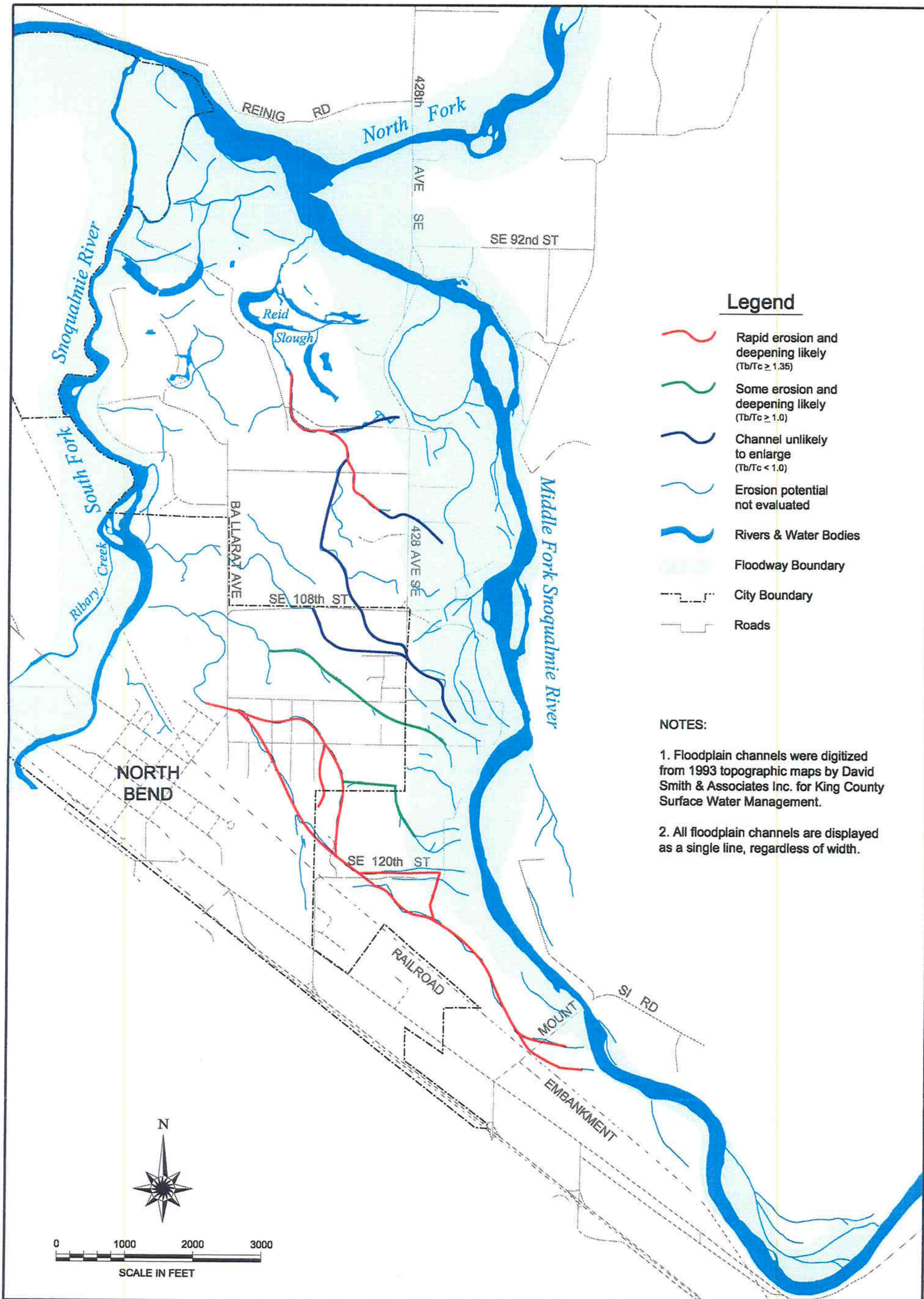
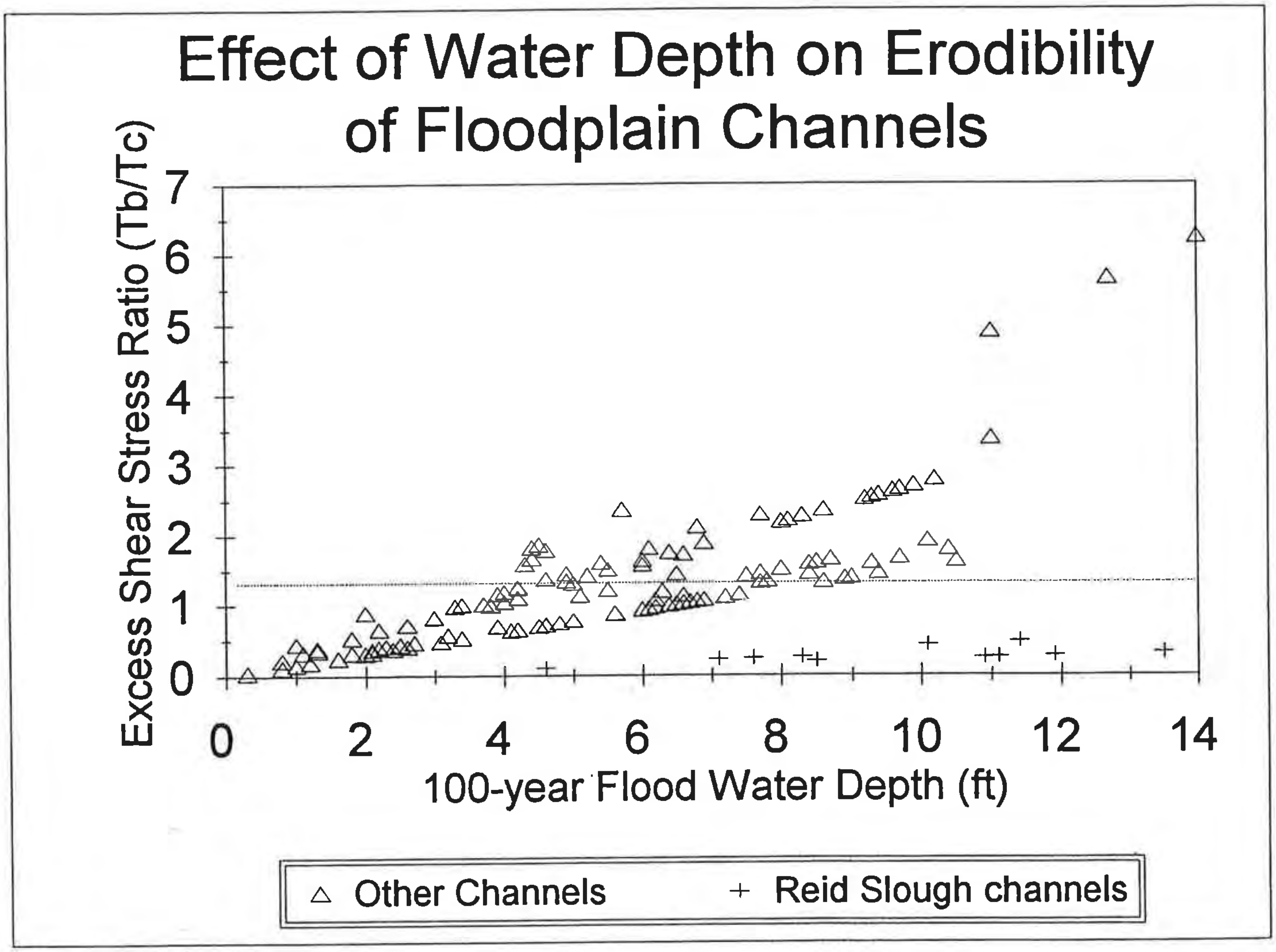


FIGURE 17

Enlargement Potential of Floodplain Channels between the Middle and South Forks
-Constant Depth at Local Slope Method-

Figure 18



Effect of Water Depth on Erodibility of Floodplain Channels
Excess Shear Stress Ratio (Tb/Tc)
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
100-year Flood Water Depth (ft)
Other Channels
Reid Slough channels

The first method (Figure 16) used local depths predicted by the model, and thus probably overpredicted depth and erosion hazard in locations far from the river. To assess the first method's sensitivity to water depth, shear stresses were recalculated using water depths one to three feet lower than predicted by the model. Of the 57 channel segments that originally had shear-stress ratios above 1.35, 13 segments (23%) fell below the 1.35 level at a one foot lower water depth and the general pattern of erosion hazards remained the same. At a three feet lower water depth, however, shear-stress ratios fell below the 1.35 level in all channels north of the SE 120th Street channel network.

Discussion

These results provide an approximate indication rather than an absolute prediction of channel enlargement hazard within the study area. The calculations do not account for trees and woody shrubs that grow in some of the channels, which reduce flow velocity and soil erodibility (although the flood model itself accounts for average vegetative roughness on the floodplain). Nor do the calculations address effects of channel obstructions such as road and driveway fills, which might reduce erosion potential in smaller floods but could undergo local erosion or be breached in larger floods. As discussed above, water depths and slopes derived from the Middle Fork flood model may not best represent actual flow conditions in these smaller channels. Moreover, the formula used to calculate shear stress assumes wide, uniform flow, a condition unlikely to be met in some of the narrower channels. Backwater from the North and South forks would probably reduce water-surface slope and hence reduce erosion potential of channels in the Reid Slough area. Despite these limitations, the results demonstrate the potential for unvegetated floodplain channels to enlarge during a large flood.

The predicted inability of overbank flows to erode most of the "parallel" channels (see Map 4), even in a 100-year flood, supports the hypothesis that these channels were formed by lateral migration of the Middle Fork Snoqualmie River. This hypothesis was suggested previously in Section 4.4.1 on the basis of channel orientation and bend geometry.

The results show that most of the cross-floodplain channels could have been formed by erosion during overbank flows rather than by channel migration. Overbank flows can exert sufficient shear stress to cut down through the floodplain and enlarge these channels, given sufficient flow depth and time. Downcutting could occur in unforested (e.g., lawns) cross-floodplain channels in a 100-year event, potentially leading to bank collapse and channel widening. These results suggest that in a large flood the Middle Fork could avulse across the floodplain to the South Fork. Depending on relative water elevations in the Middle and South forks during a flood, these flow paths could be significantly steeper than the existing Middle Fork channel (Figure 15). The river-scale dimensions of the SE 120th Street channel suggest that in the past a cross-floodplain channel did indeed enlarge enough to capture all or most of the Middle Fork's in-channel flow. It should be noted that this is likely only in a severe flood event: downcutting of cross-floodplain channels was not observed in the 1990 flood (less than a 30-year event), although flows overtopped and eroded road embankments that blocked the cross-floodplain channels.

4.5 Factors Affecting Channel Migration Rates

This section discusses factors responsible for differences in channel migration rates between the river reaches, and examines factors that have caused migration rates to change over time. This understanding can be used to predict likely future trends and the degree of channel migration hazard along the rivers. However, it must be kept in mind that many instances of channel migration are caused by random events whose location and timing cannot be predicted, such as deflection of flow against a bank by a debris jam. In addition, once bank erosion starts in a given location, it can trigger rapid channel migration downstream.

4.5.1 Causes of Spatial Differences in Migration Rates

Spatial differences in channel migration rates are caused primarily by differences in physical setting such as floodplain slope and width. These physical characteristics combine to determine a river's ability to erode and transport sediment. Bank armoring and proximity to a valley wall are other primary controls on the extent of channel migration, although they have a more local effect. Variations in sediment size and vegetation type along the river banks have a relatively small effect on channel migration rates.

4.5.1.1 Patterns of Shear Stress and Channel Stability

Most of the spatial variation in channel migration rates in the Three Forks area of the Snoqualmie River can be explained by patterns of boundary shear stress, a measure of the force available for erosion and sediment transport. Boundary shear stress is the product of flow depth, slope of the water surface, and the unit weight of water. Thus, shear stress at any given discharge is controlled by the gradient and width of the river's floodplain, the sinuosity of the river, and in some locations by narrowing of the floodplain by levees.

Because a river's ability to transport sediment depends on boundary shear stress, sediment tends to be deposited in locations where shear stress decreases rapidly in the downstream direction. Shear stress will decrease and sediment will be deposited where the channel becomes less steep or shallower downstream. Since sediment deposition causes the thalweg (the deepest part of the channel) to shift and divert flow against the banks, rapid channel migration often occurs in depositional zones (e.g., Carson, 1984). Previous studies of other King County rivers have found that rapid channel migration commonly occurs in depositional zones with rapidly declining shear stress (Dunne and Dietrich, 1978; Shannon & Wilson, 1991; Perkins, 1993). Where shear stress remains fairly constant throughout a reach of river, little net deposition or erosion will occur and the channel will tend to be stable. However, sediment will be successively deposited in gravel bars in local zones of low shear stress (typically on the inside of bends) as it moves through the reach.

In addition to declining shear stress, for sediment deposition to occur there must also be an ample supply of sediment of the relevant sizes. If shear stress declines, but still remains high enough to transport the sediment load from upstream, then no deposition occurs. Within the study reach, the Snoqualmie River transports fine sediment rapidly in suspension, so an increase in suspended sediment load (fine sand and silt) is unlikely to affect the rate of channel migration significantly. The critical sediment sizes that affect channel migration are the cobbles, gravel, and coarse sand that move as bedload and are deposited in bars within the channel margins.

Figure 19 shows shear stress, water depth and water surface gradient, computed from water surface and river bed elevations from flood studies of the Middle Fork and the mainstem Snoqualmie River (FEMA, 1995; HRI, 1995a and 1995b). There is a seven-fold downstream decrease in shear stress within the Middle Fork study area, most of which occurs in reach MF1. The decrease in shear stress is primarily due to a rapid downstream decline in water-surface gradient, which overwhelms changes in flow depth. Local increases in shear stress on the Middle Fork occur where the channel is constricted, either by bridges or between levees and the valley wall. Sediment transport capacity decreases rapidly downstream in response to declining shear stress, causing gravels to drop out and instigate channel shifting. A similar pattern occurs on the North Fork. Bedload sediment that exits the North and Middle forks drops out in the Confluence reach, a zone of even lower shear stress.

Shear stress is nearly constant through most of the Mainstem reach, but increases near SR-202 in the channel constriction just upstream from Snoqualmie Falls (NHC, 1994). The flux of bedload sediment into the Mainstem reach from the Confluence reach and the South Fork is probably less than the mainstem's transport capacity, based on computed shear stresses and the sparse depositional sites in the mainstem below the South Fork confluence.[2] The relative stability of the mainstem appears related to the low rate of sediment deposition.

Patterns of shear stress thus appear to explain the abundant gravel deposits and rapid channel migration rates in the Confluence and Middle Fork reaches, as well as the relative stability of the Mainstem reach. The downstream decrease in shear stress also accounts for the rapid downstream decline in sediment size (Figure 10, Section 3.3.2).

Shear stress patterns alone do not account for the relative stability of reaches MF2 and NF2, which contain zones of rapidly declining shear stress. The scarcity of gravel deposits indicates that, although declining, shear stress remains high enough that most sediment that enters the reach can be transported through the reach. In addition, opportunities for channel shifting are limited because parts of both reaches are held in position by armored banks or the valley wall. Similar stable zones occur in steeper, partially-confined sections with declining gradient but little sediment deposition on the Tolt, Green, and Raging rivers (Dunne and Dietrich, 1978; Shannon & Wilson, 1991; Perkins, 1993).

Rapid sediment deposition and channel migration occur in reach SF2 of the South Fork, just downstream of the leveed section of the river. Water-surface gradient is significantly lower in this reach than upstream, and water depth decreases because the flow is no longer confined by levees (Figure 20). The resulting drop in shear stress leads to rapid sediment deposition and channel shifting throughout reach SF2. Backwater from the Snoqualmie River extends up the South Fork slightly beyond reach SF1 during 10-year or larger flood events (FEMA, 1995), and probably during smaller

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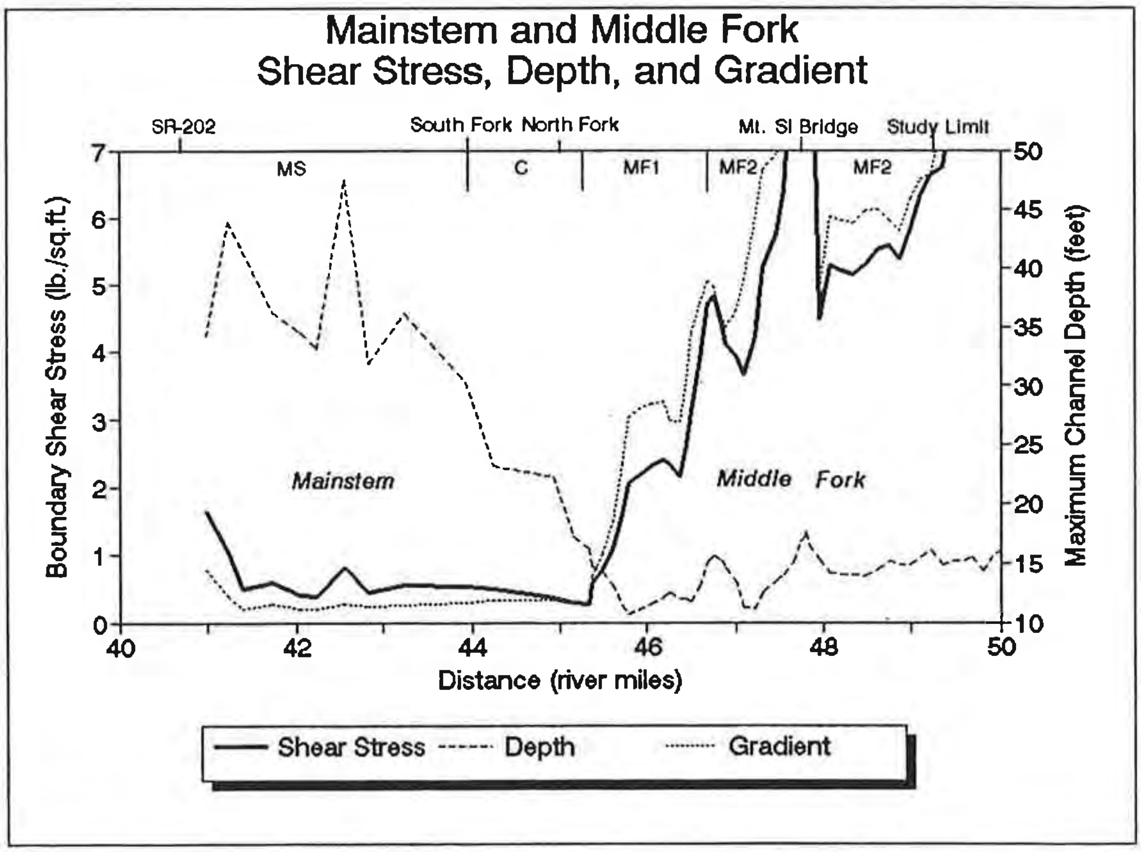
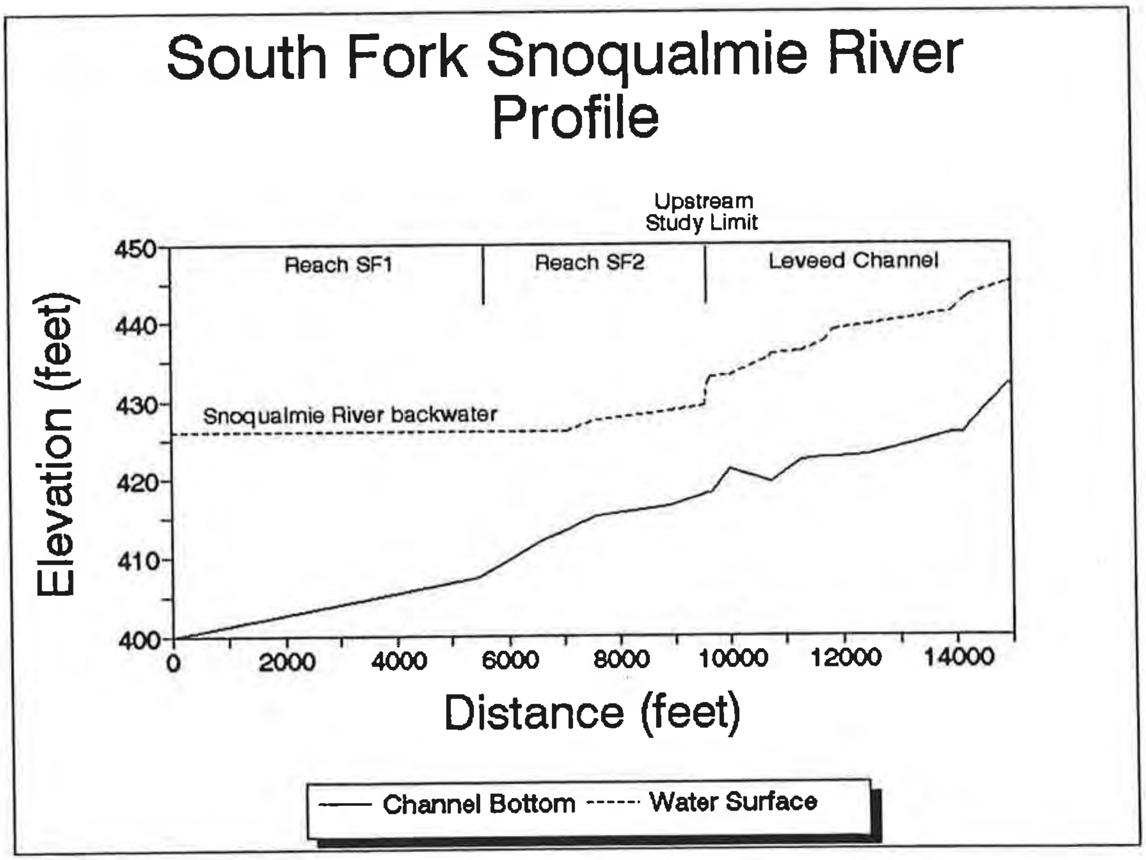
[2] Sediment transport modeling of the South Fork and mainstem Snoqualmie by Booth et al., 1991, indicates that the flux of sediment from the South Fork into the mainstem is far below the mainstem's transport capacity. Sediment transport modeling of the North Fork and Middle Fork is planned for 1996 using data from new flood studies.

Figure 19



NOTES:
Figure shows 100-year-flood water surface gradient, depth, and shear stress for the thalweg (deepest point of the channel). Values for Middle Fork are a 5-point running average. Local peaks are caused by bridges or other constrictions.
Mainstem data source: FEMA, 1995.
Middle Fork data source: HRI, 1995b.

Figure 20



Source: FEMA, 1989. Dashed line shows 100-year water surface with levees.

floods as well. The backwater causes gradient and shear stress to drop to nearly zero, and hence very little sediment transport, bedload deposition, or channel migration occur within reach SF1.

4.5.1.2 Bank Materials

The composition of the toe of a river bank controls the bank's resistance to erosion, since even strong upper bank materials will collapse if undermined (Thorne and Lewin, 1979). Sediments exposed in the toes of river banks in the study area are similar to those in adjacent bars in the river channel, whose size distributions were measured for this study (Figure 10). As described in Section 3.3.2, most banks in the three river forks are composed of sandy gravel. The median sediment diameter of the coarsest bars in the upper Middle Fork and North Fork reaches was approximately triple that of the finest bar at the confluence of the forks. Nanson and Hickin (1986) found that, for sand and gravel rivers in Canada, a 10-fold increase in the median particle size of bank sediment resulted in only a doubling of bank resistance to erosion. If the same relationship holds for the Snoqualmie River, the effect on bank erosion would be about a 30 percent increase in erodibility of the finer sediment at the forks compared to the coarser sediment upstream, with a general downstream increase in erodibility. Although this suggests that coarse bank sediment contributes to low migration rates in reaches MF2 and NF2, the change in sediment size clearly cannot account for the several-fold increase in migration rates downstream at the confluence.

Most banks in the mainstem and reach SF1 are composed of fine sand and silt, in some cases with fine gravel at the toes of the banks. The banks do not contain enough clay to render them cohesive. Based on the reasoning above, these fine-grained banks should be even more erodible than banks in upstream reaches, a prediction not in accordance with observed migration rates. As discussed above, migration rates in the mainstem and lower South Fork are highly influenced by shear stress and sediment load, so bank erodibility is in general a factor of secondary importance. Locally, however, both the South Fork and the mainstem flow past sites of former oxbow lakes and abandoned channel mouths. Studies on other meandering rivers, such as the Red and Mississippi, have shown that abandoned channels fill in with fine sediment, forming cohesive "clay plugs" that are significantly less erodible than the surrounding alluvial deposits (e.g., Thorne et al., 1991). Although only one clayey deposit was observed during this study (South Fork RM 1.7, right bank), such a clay plug probably exists just upstream from RM 44 where the downstream end of a meander bend was locked into place between 1942 and 1958 (Map 2). A side channel that branches off the South Fork now occupies this site. Other clay plugs probably exist on the mainstem, but their locations are unknown due to dense bank vegetation.

Lowest channel migration rates occur where the river abuts bedrock or riprap (large rock placed for bank protection). The effectiveness of bank armor on migration rates is assessed below in Section 4.5.2.2. River bend migration occurs when sediment is deposited in a bar on the inside of a bend, and flow concentrates against and undercuts the concave, outer bank. When bend migration causes the outer bank of a river bend to encounter resistant material of the valley wall, the river can become locked in position and a period of stability can ensue. This situation has existed in parts of the Middle Fork since early in the 20th century, and in the Confluence reach along the Reinig Road revetment since the 1960s (Map 3). However, such periods of stability can end abruptly when the river changes course and leaves the valley wall, as occurred on the Tolt River following an avulsion in the

1980s (Shannon & Wilson, 1991). Similar periods of instability could occur in the future on these rivers.

4.5.1.3 Influence of Bank Vegetation on Channel Migration

On low-gradient, high-sinuosity rivers that transport fine-grained sediment, as well as on small stream channels, bank vegetation has been found to significantly affect rates of bank erosion. These rivers differ from gravel-bed rivers such as the upper Snoqualmie River system in having significantly lower erosive stresses on their banks. Shannon & Wilson (1991) found in their study of the Tolt and Raging Rivers that naturally occurring vegetation (both deciduous riparian and second-growth conifer forests) did not prevent bank erosion in places where flow was concentrated against a bank. Very few roots penetrated deep enough to prevent scour of the lower bank. Upper sections of banks, held together by roots, were commonly cantilevered over the river. The trees and upper bank toppled into the river once scour undermined the bank completely, so that long-term rates of bank erosion were controlled by erosion of the lower bank.

To quote from the Shannon & Wilson report:

> Similar observations on the lack of effectiveness of native vegetation in stabilizing gravel river banks were made by Nanson and Hickin (1986), who pointed out that vegetation affects only the subaerial portion of the bank, and that the strength of the upper bank is irrelevant once it is undermined.
>
> Where flow depths and erosive forces are lower (e.g., banks whose toes are armored to prevent scour, banks on the opposite side of the channel from the thalweg, floodplains, and vegetated bars), roots and dense vegetation can reduce water velocity, prevent erosion, and promote deposition of sediment. In these cases, the presence of vegetation could be the controlling factor in determining whether erosion occurs during floods. In particular, vegetation may help to prevent avulsions by preventing development or enlargement of floodplain channels.

4.5.2 Causes of Temporal Channel Migration Changes

Channel migration rates decreased significantly in most reaches of the study area during the past half century, the period for migration rates were calculated. Although the pre-1942 maps were not accurate enough for calculation of migration rates, they provide evidence of dramatic changes in channel pattern (and presumably migration processes and rates) in some reaches. Some of these pattern changes continued into the post-1942 period and are related to the later decline in migration rates in those reaches.

4.5.2.1 Changes in Channel Sinuosity and Bend Geometry

Sinuosity, the ratio of channel length to valley length, is a commonly used index of river straightness. A sinuosity of 1.0 indicates a perfectly straight channel, while rivers considered to be truly meandering have sinuosities of 1.5 or greater. Sinuosity in most study area reaches has been nearly constant since at least 1942 (Table 10). The low sinuosities (1.1 to 1.4) are typical of steeper, bedload-transporting rivers with weak, non-cohesive sand or gravel banks (Schumm, 1977). The early surveys are not sufficiently detailed to determine pre-1942 sinuosity for the North or South forks, or for reach MF2 of the Middle Fork. However, scars of abandoned channels on both sides of the North Fork suggest that reach NF1 may formerly have been more sinuous (Map 4).

In the 19th and early 20th centuries, the Confluence and lower Middle Fork reaches (C and MF1) were meandering (sinuosities of 1.6 to 2.4) and had large, high amplitude bends (Table 11). During the early 20th century the large bends were truncated by cutoffs, which caused sinuosity to decline rapidly. This occurred between 1913 and 1942 on reach MF1 and between 1913 and 1960 on reach C, as shown on Figure 21. Since the 1940s these reaches have exhibited a slightly sinuous, semi-braided pattern; new bends have developed with significantly smaller wavelengths and amplitudes than the large bends that were cut off. Because of cutoffs and reductions in bend amplitude, the post-1960 meander belt in these reaches is significantly narrower than previously (Maps 1 and 2).

Although the mainstem reach (MS) as a whole was already slightly sinuous in 1865, the date of the earliest survey, the scars of large abandoned bends (Mill Pond, Meadowbrook Slough) suggest that mainstem sinuosity may have been higher sometime prior to 1865 (Map 1). Although sinuosity remained nearly constant, meander wavelength and amplitude in the mainstem upstream from the RM 42.6 railroad bridge have decreased since 1913, similar to changes in the upstream reaches.

The reasons for these post-1913 channel pattern changes in the mainstem, Confluence, and lower Middle Fork reaches are unknown. Possible causes fall in two main categories: direct alteration of these river reaches by human activities, and/or changed climatic or watershed conditions that affected flood size or sediment load. Early engineering efforts that may have promoted cutoff development and bend abandonment include dredging, blocking off channels, or diverting flows. We have no evidence of such activities, since King County records of river engineering projects only extend back to about 1960. Rivers constantly adjust their planforms, dimensions and slopes to most efficiently convey their water and sediment loads. Hence, even if human intervention originally straightened the large bends, it seems likely that the rivers would have reestablished them. Instead, new bends not constrained by bank protection have been significantly smaller, both in wavelength and amplitude.

The persistence of a straighter, less sinuous, channel pattern suggests that changes in flood size or sediment load occurred. Several studies have documented rivers changing from a high-sinuosity channel with large meander bends to a straighter (or even braided) pattern in response to increased sediment load (e.g., Schumm, 1977; Smith and Smith, 1984). Because straighter channels are steeper and have less resistance to flow, a river can transport more sediment or water by decreasing its sinuosity. Increased width is another common response to large floods or an increased sediment load.

The Snoqualmie River is unregulated and hence flood magnitude and frequency should not have changed. The limited flood records suggest that the flood regime was relatively constant throughout the time of greatest pattern change (Figures 5 to 8), although there was a large flood in 1932 during which some of the cutoffs may have formed (more recent cutoffs on these rivers have tended to be associated with moderate to large floods, as described in the next section). Although it is possible that timber harvest in the transient snow zone may have increased flood peaks of the individual river forks, a recent analysis of the entire Snoqualmie basin failed to find an increase in mainstem Snoqualmie flood

TABLE 10

Changes in Sinuosity
(channel length/valley length)

REACH	1913*	1921	1942	1958	1961	1993
MS	1.3	1.2	1.4	1.4	1.4	1.3
C	2.4	1.9	1.7	1.1	1.1	1.2
NF1	**	**	1.1	1.2	1.1	1.2
NF2	**	**	1.2	1.2	1.2	1.2
MF1	1.8	1.6	1.2	1.2	1.2	1.2
MF2	**	**	1.4	1.4	1.4	1.4
SF1	**	**	1.1	1.1	1.1	1.1
SF2	**	**	1.2	1.4	1.4	1.4

* Sinuosity of pre-1913 channels appears similar to 1913. Sinuosity was calculated using the 1913 channel map because it was more detailed, and hence presumably more accurate, than the earlier maps.

** Pre-1942 maps were not detailed enough to calculate sinuosity for these reaches.

TABLE 11

Changes in Bend Geometry

Reach	Period	Meander Wavelength (ft)	Meander Amplitude (ft)
Mainstem (upstream mile only)	1865 through 1913	4000	700 to 1000
" "	1921	2000	500
" "	1942 through 1993	1500	500 to 800
Confluence	1865 through 1921	2500 to 3000	1000 to 2000
	1942 through 1958	2000	400 to 1300
" "	1961 through 1993	1700 to 1800	400 to 500
Middle Fork 1	1865 through 1921	3400	1300
" "	1942 through 1993	1300	300 to 400

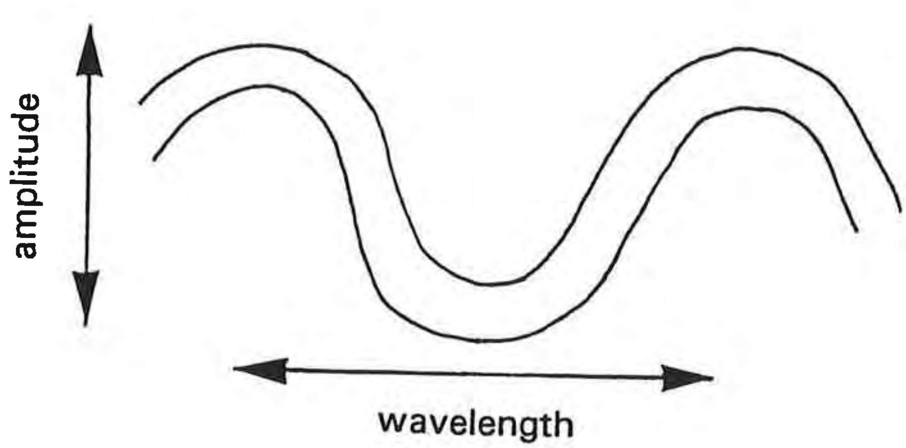
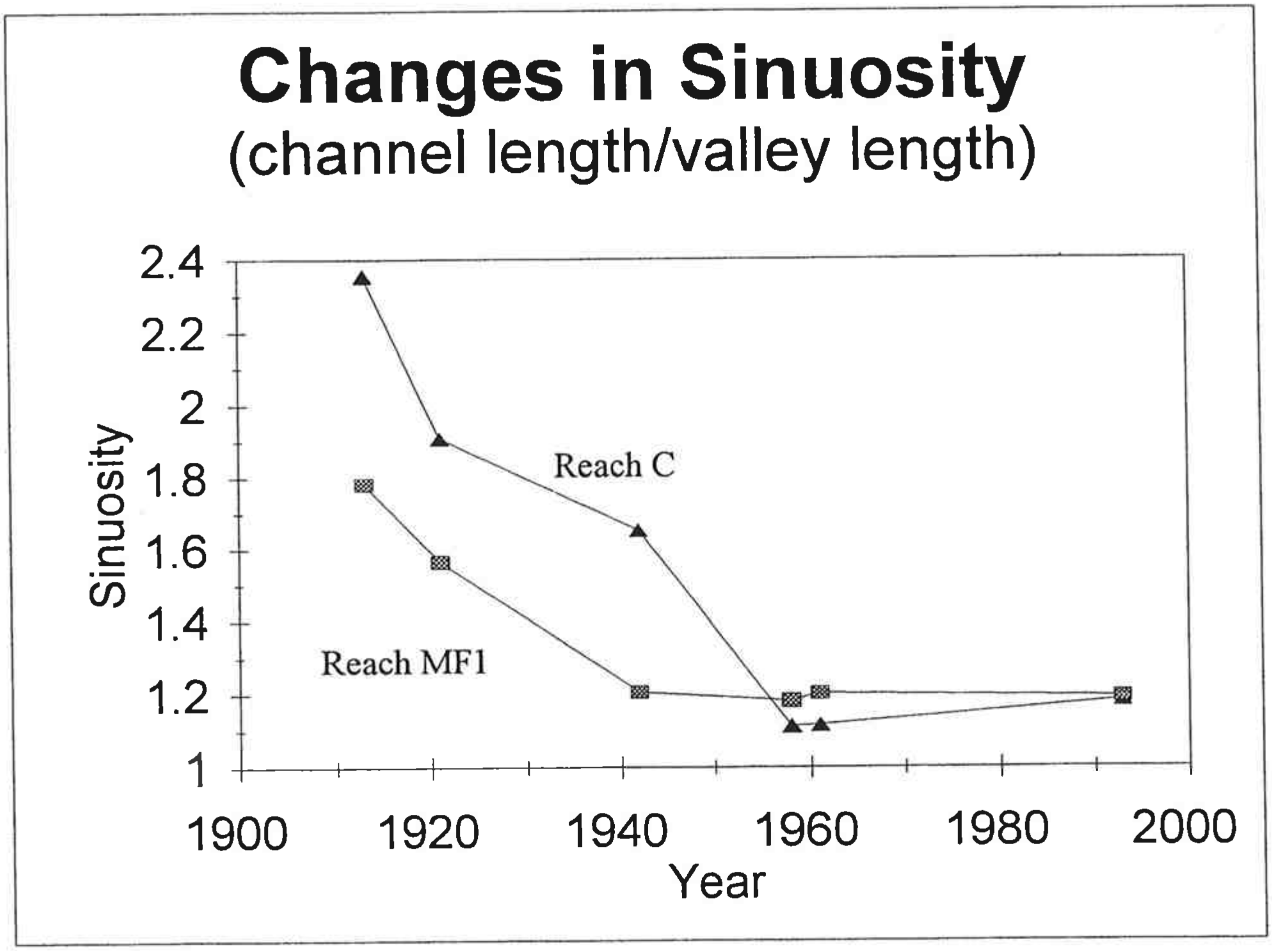


Figure 21



NOTE: Pre-1913 sinuosity appeared similar to 1913. Sinuosity was calculated using the 1913 channel map because it was more detailed, and hence presumably more accurate, than the earlier maps.

magnitude related to timber harvest (Connelly et al, 1993). The study did find that the area of recently-harvested land in the transient snow zone in the Snoqualmie Basin increased significantly between 1940 and 1960 (no land-use data were available prior to 1940), which raises the possibility that rain-on-snow flooding may have increased prior to 1940 in tributaries to the mainstem.

Increased coarse (bedload) sediment load from timber harvest is a more likely, but still speculative, cause of the channel pattern change in the Middle Fork and Confluence reaches. Railroad logging started by 1897 near North Bend and then moved up the valleys of the three forks, peaking in the 1930s and early 1940s (Northwest Archaeological Associates, 1990; USFS, 1995). The magnitude of coarse sediment load from landslides related to railroad logging is unknown, but due to minimal road construction and generally gentler terrain it was probably significantly less than from later clearcutting. Caterpillar logging, with greater land disturbance, started on Middle Fork in the 1930s. Given that the downstream rate of bedload sediment movement on these rivers is on the order of one-half to one mile per year, and that logging progressively moved up each river fork during a period of 15 to 30 years, logging may have resulted in a prolonged increase in coarse sediment delivery to the Three Forks area. Large fires in 1910 on the North Fork and in 1940 in the Pratt River drainage (a major Middle Fork tributary) could have increased sediment load as well. It is unclear whether a significant increase in bedload flux would have reached the Three Forks area yet between 1913 and 1921, when our maps show the first channel changes. It is possible that the observed channel narrowing in reach MF1 in the 1960s and 1970s may be related to passage of a sediment wave associated with upstream logging. A later round of road-based logging began in the 1960s and peaked in the 1980s, but much of the bedload sediment from that round probably has not yet reached the study area.

The links between increased sediment load, timber harvest, flood history, and observed changes in channel pattern are certainly complex and remain speculative, given the lack of a comprehensive study of sediment sources and routing for the watersheds of the three forks. However, there does not appear to be a fundamental shift in watershed conditions that would preclude the river from resuming its high-amplitude bends and wider meander belt in reaches C, MF1, and upper MS, where not constrained by armored banks. Indeed, because better timber management practices and reduced harvest rates now are presumably reducing sediment influx to the Snoqualmie forks, in future decades the Three Forks area may experience a reduction in bedload supply to closer to turn-of-the-century rates.

4.5.2.2 Causes of Temporal Changes in 1942-1993 Migration Rates

Channel migration rates in the study area have changed significantly during the past half century, as described in Section 4.3.2. With the exception of reach NF1 on the North Fork, migration rates were lower in the 1961 to 1993 period than in the 1942 to 1961 or 1942 to 1958 periods. Only in reach NF1 were channel migration rates similar before and after 1961. Migration rates declined even in sections of river without armored banks, suggesting that extensive bank armoring during the 1960s was not solely responsible for the reduction in migration rates. In addition to levee and revetment construction, other factors that potentially could have affected migration rates include flood history, gravel removal, and changes in river pattern (e.g., meandering to braided). Unlike most King County rivers, the Snoqualmie River system has no dams large enough to affect channel migration by reducing flood size or sediment delivery.

Table 12 summarizes post-1942 temporal changes in migration rates, bank armoring, and flood size for each reach. Table 12 also lists the most probable causes of migration rate changes, based on the reasoning given below. Neither bank armoring nor flood size alone explain the observed migration rate changes in most cases. On the South Fork, the decline in migration rates can be attributed to sediment removal upstream from the study area. In other cases, high channel migration rates were associated with channel pattern changes. Migration rates decreased once the new channel pattern became established.

With the exception of the large 1959 flood (WY 1960) that caused very rapid, widespread channel migration, flood size generally did not correlate well with channel migration. In the 1990 flood (WY 1991), a moderately large event with about a 20- to 30-year return period on the Middle and South forks, rapid channel migration occurred but was much more localized than in 1959. However, rapid channel migration also occurred in portions of most reaches during periods when floods were relatively small (5- to 10-year events). In some locations, channel migration rates declined significantly during periods when flood size and magnitude increased or remained steady. Although channel migration rates did not correlate well with flood size, the type of channel migration did. Four out of the five identified bend cutoffs in reach NF1 and three out of the four cutoffs on reach SF1 occurred during periods with moderate to large floods. Rapid lateral growth of meander bends in these reaches occurred during periods with smaller floods.

Numerous levees and revetments were constructed in the early 1960s in all river reaches except the South Fork, although the lower Middle and North forks (reaches MF1 and NF1) already had significant lengths of armored bank prior to 1960. In most cases bank-protection facilities stabilized the river at the site, as reflected by reduced armored-area migration rates (Table 7) compared to non-armored area rates (Table 6). Exceptions occurred in braided reaches, where rapid erosion continued opposite armored banks (Middle Fork 1, all time periods; Confluence, 1958-1961 only); and in reach NF1, where channel migration rates remained high despite extensive additional levees and revetments. In many cases, the levees and revetments also reduced average migration rates in adjacent, non-armored sections of river. To the extent that levees and revetments were preferentially built in sites experiencing severe erosion, and to the extent that they stabilized the course of the river, they reduced the likelihood of measurable rates of channel migration occurring on adjacent unprotected banks. This stabilizing effect was greatest in reaches where lateral migration is the dominant channel-migration process, such as the mainstem. .

The migration rate data suggest that levees and revetments have not destabilized adjacent sections of river, except perhaps on reach NF1 (see below). However, the results do not rule out localized bank erosion caused by levees or revetments, either immediately downstream on the same bank or farther downstream where the current is deflected to the opposite bank. Localized bank erosion on a scale of a few tens of feet is difficult to detect using aerial photographs, and even if detected, would not significantly alter the average migration rate calculated for an entire reach.

TABLE 12

CAUSES OF TEMPORAL CHANGES IN MIGRATION RATES BETWEEN 1942-1961 AND 1961-1993 PERIODS

RIVER REACH	CHANGE IN MIGRATION RATE	LENGTH OF REACH WITH BANK ARMOR ADDED (%)	CHANGE IN FLOOD SIZE	PROBABLE CAUSES OF MIGRATION RATE CHANGE
North Fork 1	up 4 %	53	down	1) pattern change occurred 2) levees caused shift of meander-belt
South Fork 1	down 69 %	0	same or up	no longer adjusting to previous pattern changes in reach and upstream
South Fork 2	down 45 %	10	same or up	1) reduced sediment load from upstream 2) absence of major pattern changes
Middle Fork 1	down 84 %	15	down 1960s, then same	1) bank armor (all bends now stable) 2) pattern change completed
Confluence	down 55 %	37	down 1960s, then same	1) pattern change completed 2) bank armor
Mainstem	down or same	50	down 1960s, then same; up in 1990	1) bank armor at bends

Discussion of Post-1942 Temporal Changes by River Reach

This section provides a more detailed discussion of the causes of temporal changes in migration rates in each reach, as summarized in Table 12.

North Fork

The North Fork experienced a significant reduction in the number and size of large floods during the post-1961 period. Seven floods of 11,000 cfs or greater at the gage occurred on the North Fork during the 1942 to 1961 period (Figure 7). No floods exceeded 11,000 cfs during the next 25 years. A period with some larger floods resumed in WY 1987, with two peaks above 12,000 cfs. Average channel migration rates for reach NF1 did not decline during the post-1961 period, despite smaller floods and extensive new levee construction. The levees caused channel migration to occur in new locations, as the river restored its meander belt width by developing new bends and shifting westward. Several bends grew rapidly during the 1960s and 1970s in the upstream part of NF1, which had previously been straightened by the Vallcuda levee. The bend growth may have been triggered by 1962 construction of the North Park levee (Map 3), which by constricting and straightening the channel in reach NF2 shifted sediment deposition downstream into reach NF1.

South Fork

Both South Fork study reaches experienced a dramatic drop in migration rates in the 1961 to 1993 period, despite an almost complete absence of bank armoring. Flood history does not explain the decline in migration rates, since peak flow data for the South Fork suggest that the number and size of large floods in the 1961 to 1993 period either increased or remained relatively constant compared to the 1942 to 1961 period[3] (Figure 8). Channel migration rates in reach SF2 were insensitive to flood size within the 1961 to 1993 period, remaining fairly constant despite a gap without floods above 9,300 cfs in the 1960s and early 1970s. On reach SF1 the decreased migration rates may be partly flow-related, however, since most of the small amount of post-1961 bank erosion occurred after 1981.

The most likely explanation for the post-1960 decline in migration rates is upstream gravel removal in the mid-1960s (see Section 3.1). A volume of gravel equivalent to about 15 years of bedload transport was removed from the South Fork to construct levees in North Bend. This probably significantly reduced sediment delivery to reach SF2, which in turn presumably reduced rates of sediment deposition and channel migration.

The higher pre-1961 rates for both South Fork reaches reflect pattern changes that occurred between 1942 and 1958. During this time, reach SF2 increased 16 percent in length as 2 new bends grew, and the effects of the changed bend alignment ricocheted downstream as far as the upstream part of reach SF1. In reach SF1, the higher 1942 to 1958 rates may also be related to adjustments of a cutoff channel that probably developed shortly before 1942. The lower 1961 to 1993 migration rates correspond to an absence of sinuosity changes.

[3] The uncertainty arises due to flows estimated by correlation with other gages, as described in Section 3.2.

Middle Fork

Average migration rates for Middle Fork reach MF1 dropped precipitously after 1961, a far greater decline than for other reaches (Tables 5a, 6a, 7a). Almost 80 percent of the reach experienced no measurable channel migration throughout the entire post-1961 period, compared to 20 percent in the pre-1961 period. Flood size and frequency on the Middle Fork have been fairly constant during the study period, although a gap without large floods occurred in the 1960s and early 1970s (Figure 6). This flood gap does not entirely explain the reduction in migration rates, however, since rapid channel shifting occurred locally throughout the 1960s and 1970s and prompted construction of additional revetments in 1973 (Map 3). Even the three moderately large floods between WY 1978 and WY 1991 caused only local channel migration and widening. Reach MF1 thus appears to have become fundamentally more stable.

The decline in Middle Fork migration rates appears to have two causes: bank armoring and the cessation of channel pattern change. Although levees and revetments were added to only 15 percent of the reach after 1960, these additions resulted in the river being stabilized at the outside of every bend by either bank armor or the valley wall. Much of the 1942 to 1958 migration was caused by the river's adjustments to the earlier cutoff of a large bend, i.e., subsequent widening and realignment of the cutoff channel. Once these adjustments were completed, migration rates declined.

Confluence

Migration rates in the Confluence reach appear to have declined for similar reasons as on the Middle Fork: the cessation of channel pattern changes and (to a lesser extent) bank armoring. The 1940s and 1950s were a period with rapid bend growth and cutoffs. The lower post-1961 migration rates reflect the change to a straighter, more braided, channel pattern. As discussed above in Section 4.5.2.1, the cause of this fundamental shift to a straighter channel in the lower Middle Fork and the Confluence reach is unknown. Unlike the Middle Fork, in the Confluence reach widespread channel migration continued during the post-1961 period. Bank erosion occurred along 84 percent of the reach, but channel migration rates declined because the river moved shorter distances commensurate with the smaller meander bends. Bank armoring has reduced migration rates less in the Confluence reach than on the Middle Fork. Although nearly half of the Confluence reach is armored, all the revetments are on the north edge of the historic meander belt and the river remains unconstrained to the south. Nevertheless, for several decades the Reinig Road revetment has helped stabilize the downstream part of the reach at the outside of a bend. Floods in the Confluence reach are dominated by flows from the larger Middle Fork, with smaller contributions from the North Fork. As on the Middle Fork, the lower 1961 to 1993 migration rates cannot be explained by the absence of large floods in the 1960s and early 1970s. In fact, more land was eroded between 1961 and 1970 than between 1981 and 1993 despite larger floods in the latter period.

Mainstem

Although migration rates are nearly the same for the pre-1961 and post-1961 periods, the calculated 1942 to 1958 migration rates are probably too low due to difficulties with 1942 photo registration. It is therefore likely that the Mainstem migration rates actually declined in the post-1961 period. This is supported by the river's behavior in the two largest floods of record. The 1990 flood (WY 1991) greatly exceeded the discharge of the previous flood of record in 1959 (WY 1960; see Figure 5). Yet our mapping based on aerial photographs shows that Mainstem channel migration was both more widespread and more severe in the smaller 1959 flood, which occurred prior to most of the revetment construction. It seems likely that the armored banks on the outsides of most bends have had a stabilizing effect on this reach of river, in which lateral migration is the dominant migration process.

5.0 HAZARDS FROM FUTURE CHANNEL MIGRATION

The results presented in Section 4.0 were used to predict the probable future limits of channel migration within the Snoqualmie Three Forks study area. Based on these predictions, land in the valley floor was classified according to its relative level of hazard from channel migration. The resulting hazard maps are shown on Sheets 5 and 6.

5.1 Methodology for Predicting Limits of Future Channel Migration

The approach used to predict probable limits of future migration is based on a simple premise: that future rates and types of channel migration in each river reach will, on average, be similar to past behavior under the same water and sediment discharge regime. This approach was chosen in preference to models that attempt to predict migration of individual river bends based on their curvature. Such models are inaccurate at best, and are particularly ill-suited for long prediction periods and for rivers with rapidly changing channel patterns. Cutoffs and rapid lateral migration cause meander bends in most reaches of the study area to be short lived, except where bends are locked into position by the valley wall or armored banks. Accordingly, analyzing the direction and rate of growth of individual bends based on their curvature would not be useful for determining long-term channel migration hazard zones.

The basic elements of the prediction methodology are as follows. First, the geologically-based outer limits of future channel migration were determined based on historic meander belt width, measured bend amplitudes, and potential avulsion sites for each reach, ignoring existing or potential revetments and levees (Unconstrained Channel Migration Hazard Map, Map 5). Recognizing that features such as major roads and subdivisions will very likely continue to be protected from bank erosion, the natural limits of channel migration in Map 5 were then scaled back to produce a Mitigated Channel Migration Hazard Map (Map 6). The Mitigated Hazard zone was subdivided into zones of Severe and Moderate Hazard, using calculated historic channel migration rates. The following sections explain these procedures in more detail.

5.1.1 Predicting Probable Unconstrained Limits of Channel Migration (Map 5)

Probable limits of future channel migration **in the absence of revetments and levees** were predicted based upon meander belt widths and bend amplitudes of former river channels. The resulting Unconstrained Channel Migration Hazard Zone is shown on Map 5.

The Snoqualmie River system has no dams that alter sediment and water discharge. Pattern changes in the Confluence and lower Middle Fork reaches during the past 50 years are suggestive of increased sediment discharge that may be related to timber harvest (Section 4.5.2.1). During the next century, sediment discharge can be expected to fluctuate in response to timber harvest cycles and other factors. Therefore, we assume that large amplitude bends will develop again in these reaches. Hence, for predicting channel migration during the next century we can assume that all former river channels on the floodplain, no matter what their age, represent the meander belt of the river.

Table 13 shows the meander belt widths and bend amplitudes used to predict probable limits of future channel migration in the absence of revetments and levees. For meander belt width of each reach, we used the maximum valley width occupied by all river channels shown on Maps 1 and 2. For bend amplitude, we used the median amplitude of meander bends that grew in each reach. We assumed that the river could, at any point along its course, grow a new bend of the amplitude specified in Table 13. The migration hazard zone was extended to the specified amplitude from both edges of the 1993 active channel, unless it encountered the edge of the morphologic floodplain (a valley wall, high terrace, or alluvial fan). Where this occurred, the hazard zone was extended farther in the opposite direction if necessary to achieve the specified meander belt width. For simplicity, it was assumed that the channel would migrate outward at right angles to the edge of the existing active channel. While this is not strictly accurate, it produces a hazard band of a reasonable width, and a more detailed treatment would be unrealistic due to the changing geometry of river bends.

The river was also assumed to shift into parallel floodplain channels (defined in Section 4.4.1) with a high avulsion potential: creeks and well-defined former channels that are flooded deeply and frequently (at least once every two to three years), diverge from the main channel in a downstream direction, and are (or could become) directly connected to the river. Potential avulsion channels were identified on aerial photographs or topographic maps and confirmed on the ground. The river was assumed to laterally migrate the specified distance from these channels as well. Consequently, in the vicinity of avulsion sites, the resulting hazard zone can be significantly wider than the specified minimum width for the meander belt.

Potential avulsion channels from the Middle Fork to the South Fork or Confluence reaches were mapped separately, since they cross the floodplain between the meander belts delineated by the methodology described above. Cross-floodplain channel systems likely to undergo rapid enlargement during a 100-year flood (see Section 4.4.2, Figures 16 and 17) were mapped with a minimum width of 200 feet, the typical width of the relict cross-floodplain channels and of the Middle Fork. Cross-floodplain channel systems likely to undergo less severe erosion were mapped with a minimum width of 100 feet. Existing channel widths were used where they exceeded these minimum widths.

The resulting hazard zones (unconstrained by bank armoring or other engineering works) cover the traces of all the river channels depicted on historic maps and photographs dating from 1865 to 1993. The resulting hazard zones also cover all river channel scars of unknown age, with the exception of the upper end of the East Fork of Kimball Creek.

5.1.2 Delineation of Mitigated Hazard Zones (Map 6)

The unconstrained, natural limits of channel migration shown on Map 5 were scaled back to the boundaries of major roads, developed areas, revetments, levees, and proposed Three Forks Park trails that are likely to be protected from future bank erosion. The resulting migration hazard zone is shown on the Mitigated Channel Migration Hazard Map (Map 6). Table 14 lists features that were assumed to be fixed boundaries beyond which channel migration will be prevented. (Refer to Map 3 for names and locations of existing revetments and levees.) Armored banks protect many of these features already, and it can be assumed that additional revetments will be constructed to protect these features as necessary.

TABLE 13

MEANDER BELT WIDTHS AND BEND AMPLITUDES USED TO DEVELOP CHANNEL MIGRATION HAZARD MAPS

River Reach	UNCONSTRAINED HAZARD MAP Minimum Meander Belt Width (ft)	 Bend Amplitude (ft)	MITIGATED HAZARD MAP Severe Hazard Erosion Width (ft)
Mainstem	4100	1000	165
Confluence	4100	1500	625
Middle Fork 1	2000 (2900 downstream of 328th Ave.)	600 (1300 downstream of RM 46)	285
Middle Fork 2	2000 (900 upstream of Mt. Si Bridge)	550	100
North Fork 1	2100	450	240
North Fork 2	800 (wider downstream)	250	100
South Fork 1	1600	200	100
South Fork 2	2500	400	280
Kimball River	2000	1500	N/A

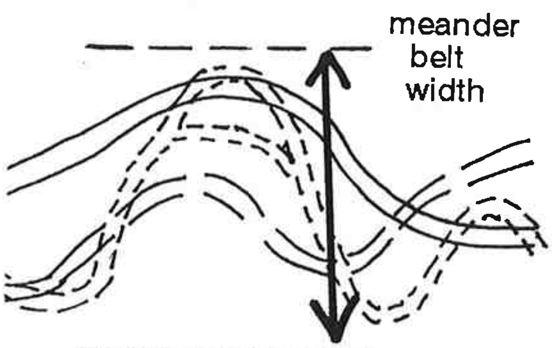


TABLE 14

Assumed Boundaries to Channel Migration

<u>Mainstem and Confluence</u>
SR 202
Downtown Snoqualmie residential and commercial development
Mill Pond Road*
Former BN Railroad bridge and embankment (King County trail)
Reinig Road
Wasechter revetment

<u>Middle Fork</u>
428th Avenue SE (road and bridge)
Old Norman bridge
Lower Norman revetment
Upper Norman revetment (north of DNR land only)
Mason-Thorson-Ells levee
Former BN Railroad bridge and embankment (King County trail)
SE Tanner Road
North Bend Way

<u>North Fork</u>
428th Avenue SE (road and bridge)
Reinig Road
Shake Mill L revetment
Tarp levee
North Park levee
Shake Mill R levee*
Burhans levee*
Vallcuda levee (on setback alignment; excludes upstream 600 feet)*
Rockridge revetment*

<u>South Fork</u>
Former BN Railroad bridge and embankment (King County trail)
City of North Bend levees and bridges

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*Considered an effective boundary to channel migration for the Severe-Hazard zone only.

NOTE: Refer to Map 3 for levee and revetment locations.

As noted on Table 14, certain features were considered effective boundaries only for mapping the Severe Hazard zone (Section 5.1.3). For the more extensive channel migration depicted as the Moderate Hazard zone, some North Fork levees would be outflanked by upstream channel migration. The privately maintained Rockridge revetment on the North Fork was considered ineffective for the Moderate Hazard scenario because of the high risk of avulsion into Tate Creek if it fails. Also included in the Moderate Hazard zone is land north of Mill Pond Road (reach MS) that may serve as a future flood relief channel (NHC, 1994).

Levees and revetments not listed in Table 14 were not considered permanent barriers to channel migration. Most of these short, discontinuous facilities are subject to breaching or overtopping (Mason-Thorson Extension, Upper Norman (south portion), Vallcuda (upstream 600 feet)); and/or damage from avulsions or upstream bank erosion (Kimball Creek, Pratt, Groin, Proctor, Duprells, Scott, Circle River Ranch, Schodde). The King County Flood Hazard Reduction Plan (FHRP) calls for removing the Moskvin and Upper Norman facilities on the Middle Fork. Both facilities are located within the floodway and constrict flow (King County, 1993, Appendix B). Consistent with FHRP policies, other river facilities that protect undeveloped land were assumed not to be maintained (e.g., Pearson) and a portion of the Vallcuda levee was assumed to be set back from the river. Meadowbrook Bridge may be closed if Mill Pond Road is relocated in conjunction with potential construction of a flood relief channel (NHC, 1994).

5.1.3 Delineation of Severe and Moderate Hazard Zones (Map 6)

Obviously the risk of channel migration is not equal within the entire mapped hazard zone. The probability of the river moving to a particular site within the hazard zone is greatest for sites near the river or near a former channel that the river is likely to reoccupy. Accordingly, we subdivided the Mitigated Hazard zone into zones of Severe and Moderate channel migration hazard. To do so, we used historic channel migration rates in a manner similar to that used for migration hazard mapping on the Green River (Perkins, 1993), Tolt and Raging Rivers (Shannon & Wilson, 1991) and the Yakima River (Dunne et al., 1976).

Based on past behavior, the channel pattern of most river reaches will change completely in much less than 100 years. Where not confined by a valley wall or a high terrace, the river can migrate in either direction from its present position. Therefore, instead of selecting areas most likely to erode based on the current river pattern, we applied average migration rates uniformly throughout the length of each reach.

To define the Severe Hazard zone, we assumed that during a 100-year period each river reach would migrate at an appropriate historic eroding-area rate (Table 5b) for 50 years in each direction from its present position. A similar procedure was used to map "High-Hazard" zones on the Green, Tolt and Raging Rivers, with the exception that average migration rates that included non-eroding areas (equivalent to Table 5a) were used on the latter two rivers. A weighted average of the 1942 to 1961 and 1961 to 1993 migration rates was used for reaches MS, NF1, SF1, and SF2. For reaches C and MF1, higher migration rates from the 1942 to 1958 period were used to reflect the likelihood that formerly more sinuous behavior could resume, and also because some existing Middle Fork bank protection facilities may be abandoned (Table 14).

Average migration rates were not calculated for reaches MF2 and NF2 because the amount of post-1942 channel migration was within the range of potential mapping errors. Maximum bank erosion distances in the 1959 flood were 60 feet and 80 feet, respectively, in reaches MF2 and NF2 (Table 8). On reach MF2, longer term local erosion rates are on the order of 1.0 to 2.0 feet per year (Table 9). For these reaches, the Severe Hazard zone was conservatively defined as 100 feet from the bank, the standard King County Sensitive Areas Ordinance (SAO) buffer for Class 1 streams.

The distance of lateral migration in each direction was calculated by multiplying the average annual migration rate for each reach by 50 years, giving the widths shown in the right-hand column of Table 13. The resulting setbacks from the 1993 active channel, and from channels with a high avulsion potential, range from 100 to 625 feet.

As for the Unconstrained Hazard map, the river was also assumed to shift into parallel floodplain channels with a high avulsion potential (see Section 5.1.1). The river was assumed to migrate laterally the specified distance from these channels as well. Consequently, in the vicinity of avulsion sites the resulting hazard zone can be significantly wider than the specified minimum width for the meander belt.

The Moderate Hazard zone shown on Map 6 was defined by default as all land between the outer boundary of the Severe Hazard zone and the outer boundary of the Mitigated Hazard Zone (section 5.1.2).

5.2 Channel Migration Hazard Maps

The channel migration hazard maps show areas at various levels of risk from channel migration, as predicted by the methodology described in Section 5.1. Map 5 shows the probable extent of channel migration if the rivers were unconstrained by revetments and levees. Map 6 shows the Mitigated Hazard zone, assuming that major roads, bridges, and subdivisions will continue to be protected from bank erosion. The Mitigated Hazard zone is subdivided into zones of Severe and Moderate Hazard.

The Severe Hazard zone on Map 6 covers virtually all areas occupied by the rivers between 1942 and 1993 except areas protected from bank erosion. In areas prone to channel switching (avulsions), the Severe Hazard zone covers a considerably wider area than the 1942 to 1993 meander belt. The Severe Hazard zone is contained within the currently mapped FEMA floodway (FEMA, 1995) in most reaches, but extends well beyond the floodway along the South Fork and the south side of the Confluence reach. The boundaries of this hazard zone, determined by extrapolating historic migration rates into the future, represent the most probable extent of channel migration in the next 100 years. However, the Severe Hazard zone predictions were based on migration rates from a half century measurement period, which may prove to be too short for accurate extrapolation of long-term river behavior. Also, bank erosion is a function of flow, the timing and magnitude of which cannot be predicted with specificity. It is therefore possible that within the next century, channel migration will extend beyond the Severe Hazard zone into the Moderate Hazard zone.

The more extensive Unconstrained Hazard zone (Map 5) was determined based on the physical dimensions of river meanders, rather than extrapolation of migration rates into the future. The resulting hazard zone covers all river channels known from historic sources dating back to 1865, as well as almost all river channel scars of unknown age. Accordingly, it represents the probable limits of unconstrained channel migration over a period of somewhat more than a century but probably less than two centuries (channel scars are unlikely to survive this long without infilling by overbank sediment). The Moderate Hazard zone on Map 6 scales back the Unconstrained Hazard zone to reflect the effects of bank armoring and other engineering works.

Avulsions (sudden channel changes to a new location) are triggered by random, unpredictable events such as log jams, landslides, large floods, and upstream changes in river position, so it is not possible to predict when or if an avulsion will occur at each potential avulsion site. Because the mapping procedure conservatively assumed that avulsions would occur at all high potential sites, it is likely that some areas within both the Moderate Hazard and Severe Hazard zones will not be occupied by the river during the next century. The mapped channel migration limits should therefore be used as an indication of relative hazard, rather than a precise prediction of the time at which the river will reach a given location.

On the other hand, there is a low, but real, possibility that the river could occupy portions of the valley floor beyond the limits of the Moderate-Hazard zone shown on Map 6. Levees and revetments could fail, flow could be diverted around bridges blocked by debris dams, and avulsions could occur in unanticipated locations. Accordingly, all unshaded areas of the valley floor, excluding high terraces, should be considered to have a low risk of encroachment by channel migration. This is consistent with morphological evidence that the rivers have previously moved across the whole valley floor, such as embayments in the valley walls, a flat floodplain underlain by alluvial gravels, numerous floodplain channels with the shape of meander bends, and recent movement of the South Fork to a part of the valley floor not occupied by the river for at least a century.

Potential avulsion channels between the Middle Fork and the South Fork or Confluence reach are shown as a separate category on the hazard maps because they were delineated using a separate methodology and may warrant a different regulatory approach. For the most part these channels lie outside the meander belts of the rivers and the currently mapped FEMA floodways. Because the Mason-Thorson-Ells levee reduces flood flow into two of the potential avulsion channels, the Mitigated Hazard map (Map 6) shows fewer Avulsion Hazard channels than the Unconstrained Hazard map (Map 5). Map 6 also shows no channel migration hazard in former river channels of the Kimball Creek system, due to the South Fork levees and northward diversion of most South Fork overbank flows by a railroad embankment. The probability of an avulsion into these channels is considered moderate, due to their infrequent occurrence.

The hazard maps do not show landslide hazards caused by steepening and undercutting of slopes by the river. The valley wall, terraces, and alluvial fans were considered limits to channel migration for the purposes of this study. However, where not underlain by competent bedrock, these areas could potentially become landslide hazards if and when the river reaches them.

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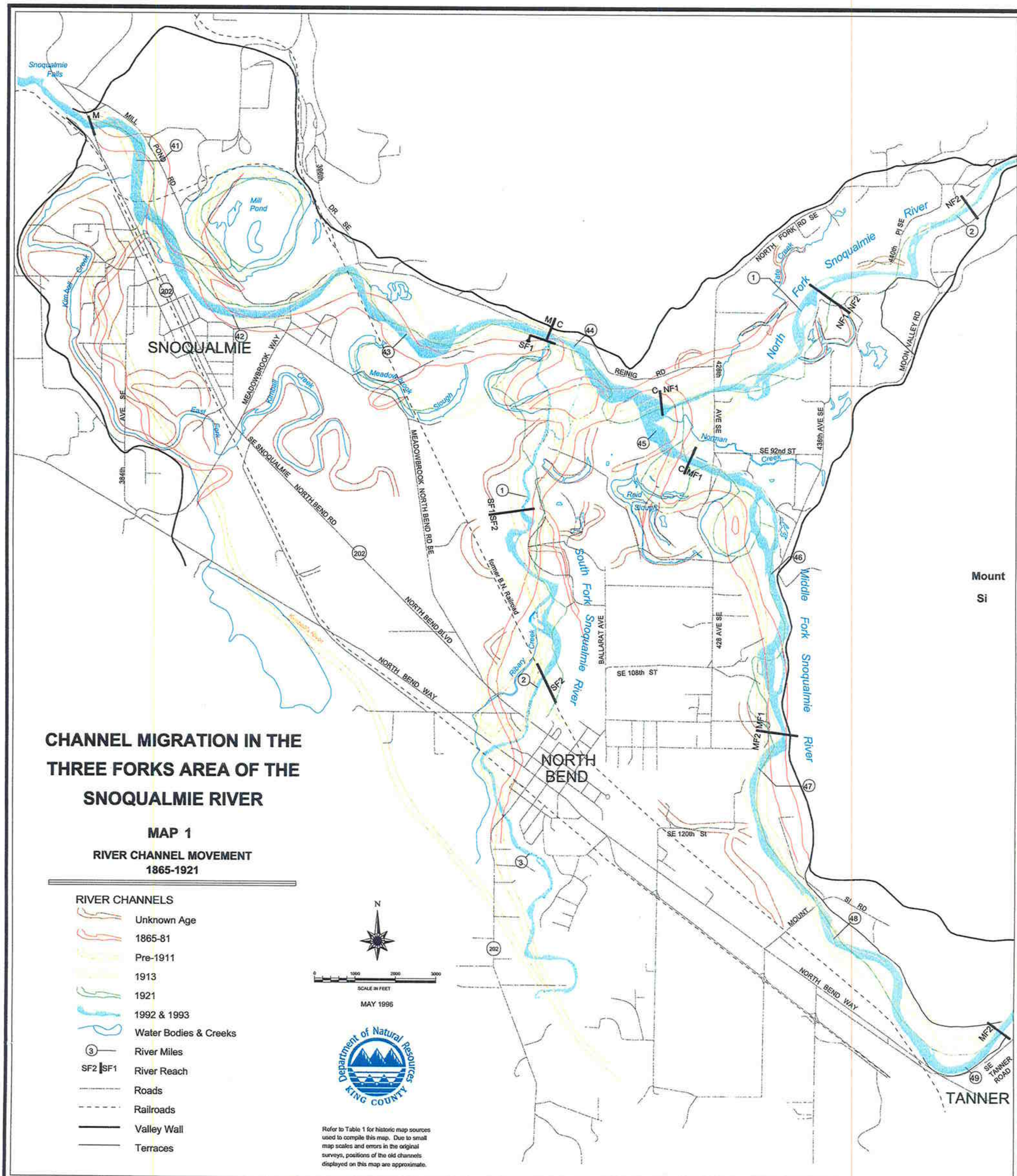
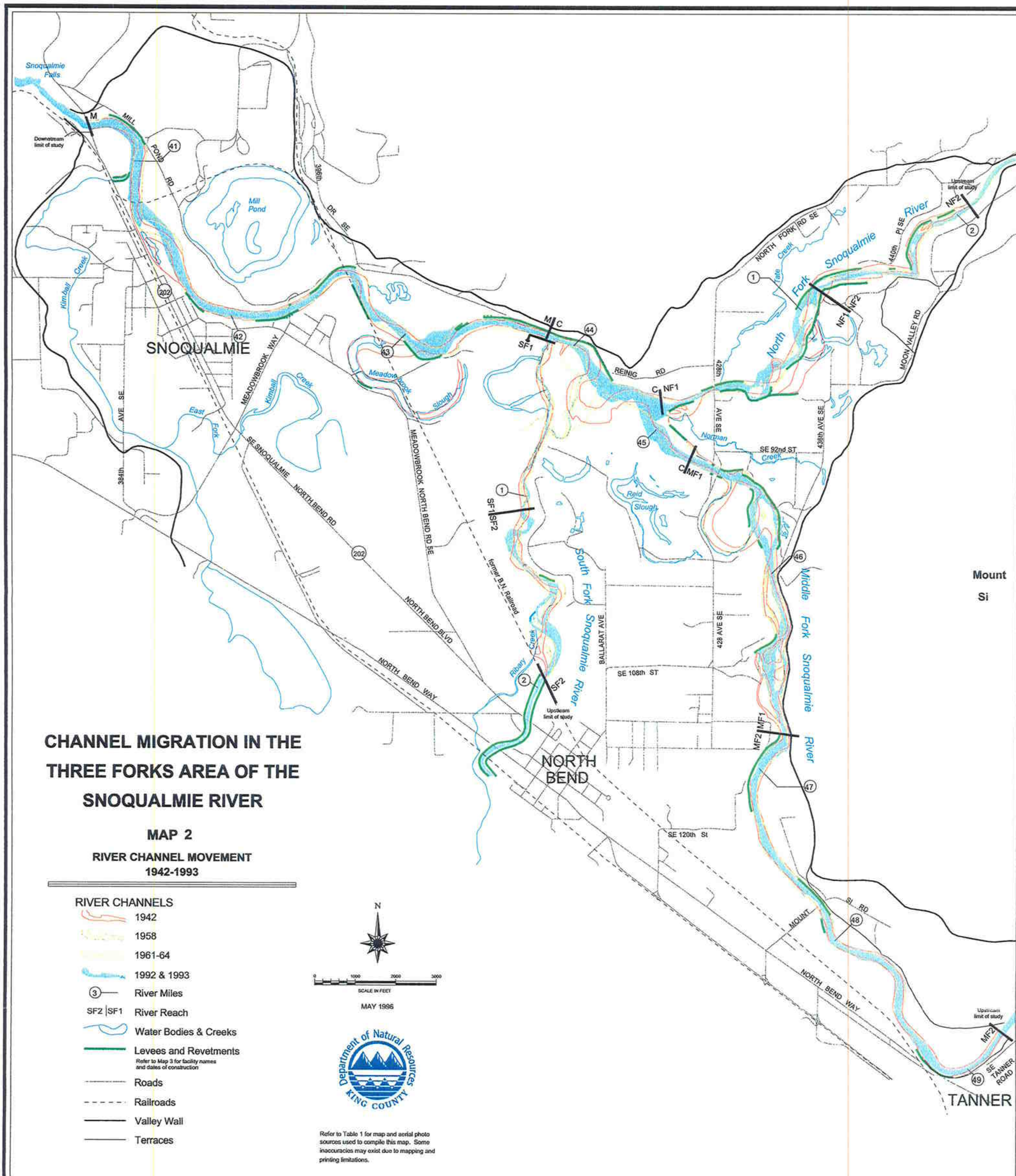
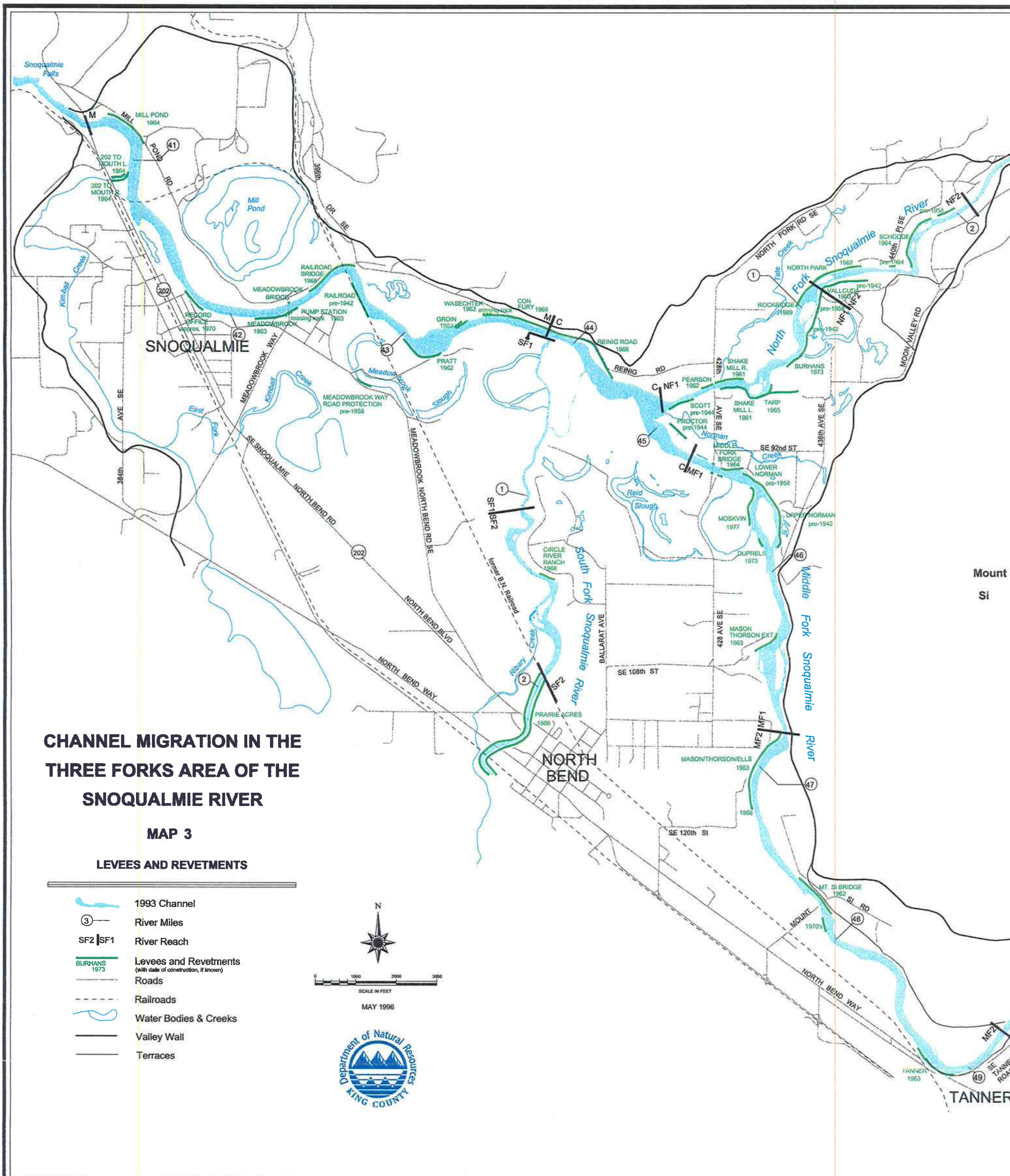
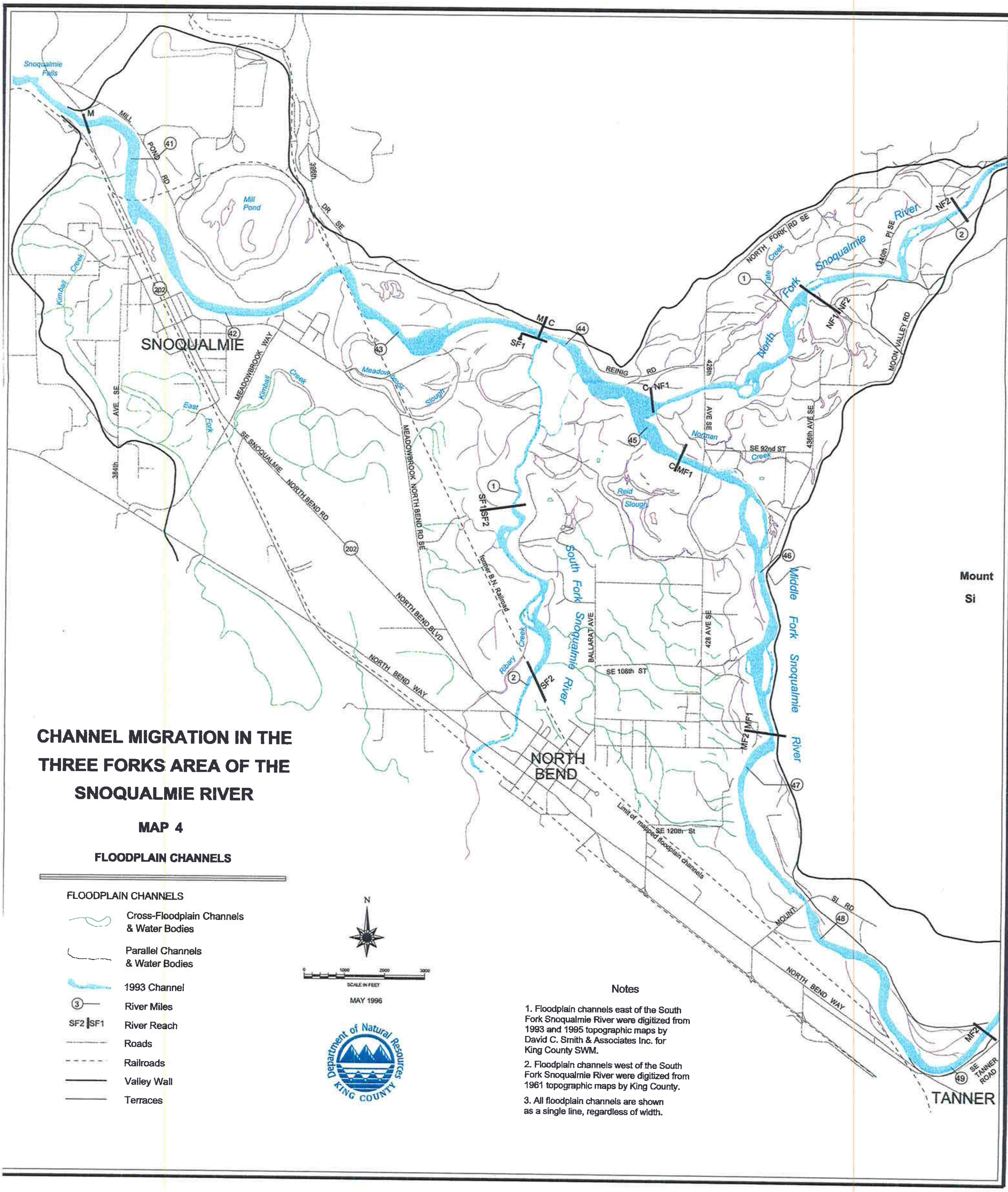

CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER
MAP 1
RIVER CHANNEL MOVEMENT 1865-1921
RIVER CHANNELS
Unknown Age
1865-81
Pre-1911
1913
1921
1992 & 1993
Water Bodies & Creeks
River Miles
River Reach
Roads
Railroads
Valley Wall
Terraces
N
SCALE IN FEET
MAY 1996
Department of Natural Resources
KING COUNTY
Refer to Table 1 for historic map sources used to compile this map. Due to small map scales and errors in the original surveys, positions of the old channels displayed on this map are approximate.
Snoqualmie Falls
SNOQUALMIE
NORTH BEND
TANNER
Mount Si
Mill Pond
MILL POND RD
396th DR SE
MEADOWBROOK WAY
SE SNOQUALMIE NORTH BEND RD
MEADOWBROOK NORTH BEND RD SE
NORTH BEND BLVD
NORTH BEND WAY
former B.N. Railroad
BALLARAT AVE
SE 108th ST
SE 120th St
428 AVE SE
436th AVE SE
SE 92nd ST
REINIG RD
NORTH FORK RD SE
MOON VALLEY RD
MOUNT SI RD
SE TANNER ROAD
384th AVE SE
Kimball Creek
Meadowbrook Slough
East Fork
Norman Creek
Reid Slough
Ribary Creek
Tate Creek
South Fork Snoqualmie River
North Fork Snoqualmie River
Middle Fork Snoqualmie River
Kimball Creek


CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER
MAP 2
RIVER CHANNEL MOVEMENT 1942-1993
RIVER CHANNELS
1942
1958
1961-64
1992 & 1993
River Miles
SF2 | SF1 River Reach
Water Bodies & Creeks
Levees and Revetments
Refer to Map 3 for facility names and dates of construction
Roads
Railroads
Valley Wall
Terraces
N
SCALE IN FEET
MAY 1996
Department of Natural Resources
KING COUNTY
Refer to Table 1 for map and aerial photo sources used to compile this map. Some inaccuracies may exist due to mapping and printing limitations.
Snoqualmie Falls
Downstream limit of study
Upstream limit of study
SNOQUALMIE
NORTH BEND
TANNER
Mount Si
Mill Pond
Kimball Creek
East Fork
Meadowbrook Slough
Reid Slough
Norman Creek
Ribary Creek
Tate Creek
South Fork Snoqualmie River
Middle Fork Snoqualmie River
North Fork Snoqualmie River
MILL POND RD
396th DR SE
MEADOWBROOK WAY
384th AVE SE
SE SNOQUALMIE NORTH BEND RD
MEADOWBROOK NORTH BEND RD SE
former B.N. Railroad
NORTH BEND BLVD
NORTH BEND WAY
BALLARAT AVE
SE 108th ST
SE 120th St
REINIG RD
428th AVE SE
436th AVE SE
SE 92nd ST
NORTH FORK RD SE
440th Pl SE
MOON VALLEY RD
MOUNT SI RD
SE TANNER ROAD
202
41
42
43
44
45
46
47
48
49
M
C
SF1
SF2
NF1
NF2
MF1
MF2



CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER
MAP 3
LEVEES AND REVETMENTS
1993 Channel
River Miles
River Reach
Levees and Revetments
(with date of construction, if known)
Roads
Railroads
Water Bodies & Creeks
Valley Wall
Terraces
N
SCALE IN FEET
MAY 1996
Department of Natural Resources
KING COUNTY
Snoqualmie Falls
SNOQUALMIE
NORTH BEND
TANNER
Mount Si
Mill Pond
MILL POND 1964
202 TO MOUTH L. 1964
202 TO MOUTH R. 1964
RAILROAD BRIDGE 1966
MEADOWBROOK BRIDGE
RAILROAD pre-1942
PUMP STATION missing rock 1963
RECORD OFFICE approx. 1970
MEADOWBROOK 1963
WASECHTER 1963 missing rock
CON FURY 1969
GROIN 1963
PRATT 1962
MEADOWBROOK WAY ROAD PROTECTION pre-1958
REINIG ROAD 1966
PEARSON 1962
SHAKE MILL R. 1961
SHAKE MILL L. 1961
TARP 1965
SCOTT pre-1944
PROCTOR pre-1944
MIDDLE FORK BRIDGE 1964
LOWER NORMAN pre-1958
UPPER NORMAN pre-1942
MOSKVIN 1977
DUPRELS 1973
MASON THORSON EXT 1963
MASON/THORSON/ELLS 1963
1968
MT. SI BRIDGE 1962
1970's
TANNER 1963
CIRCLE RIVER RANCH 1966
PRAIRIE ACRES 1966
NORTH PARK 1962
ROCKRIDGE 1989
VALLCUTS 1993
pre-1942
pre-1958
BURHANS 1973
SCHODDE 1964
North Fork Snoqualmie River
Middle Fork Snoqualmie River
South Fork Snoqualmie River
Kimball Creek
East Fork
Meadowbrook Slough
Reid Slough
Norman Creek
Tate Creek
Ribary Creek
SE 92nd ST
SE 108th ST
SE 120th St
NORTH FORK RD SE
MOON VALLEY RD
REINIG RD
MEADOWBROOK WAY
MEADOWBROOK NORTH BEND RD SE
SE SNOQUALMIE NORTH BEND RD
NORTH BEND BLVD
NORTH BEND WAY
MOUNT SI RD
BALLARAT AVE
428 AVE SE
436th AVE SE
384th AVE SE
former B.N. Railroad
SE TANNER ROAD



CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER

MAP 4

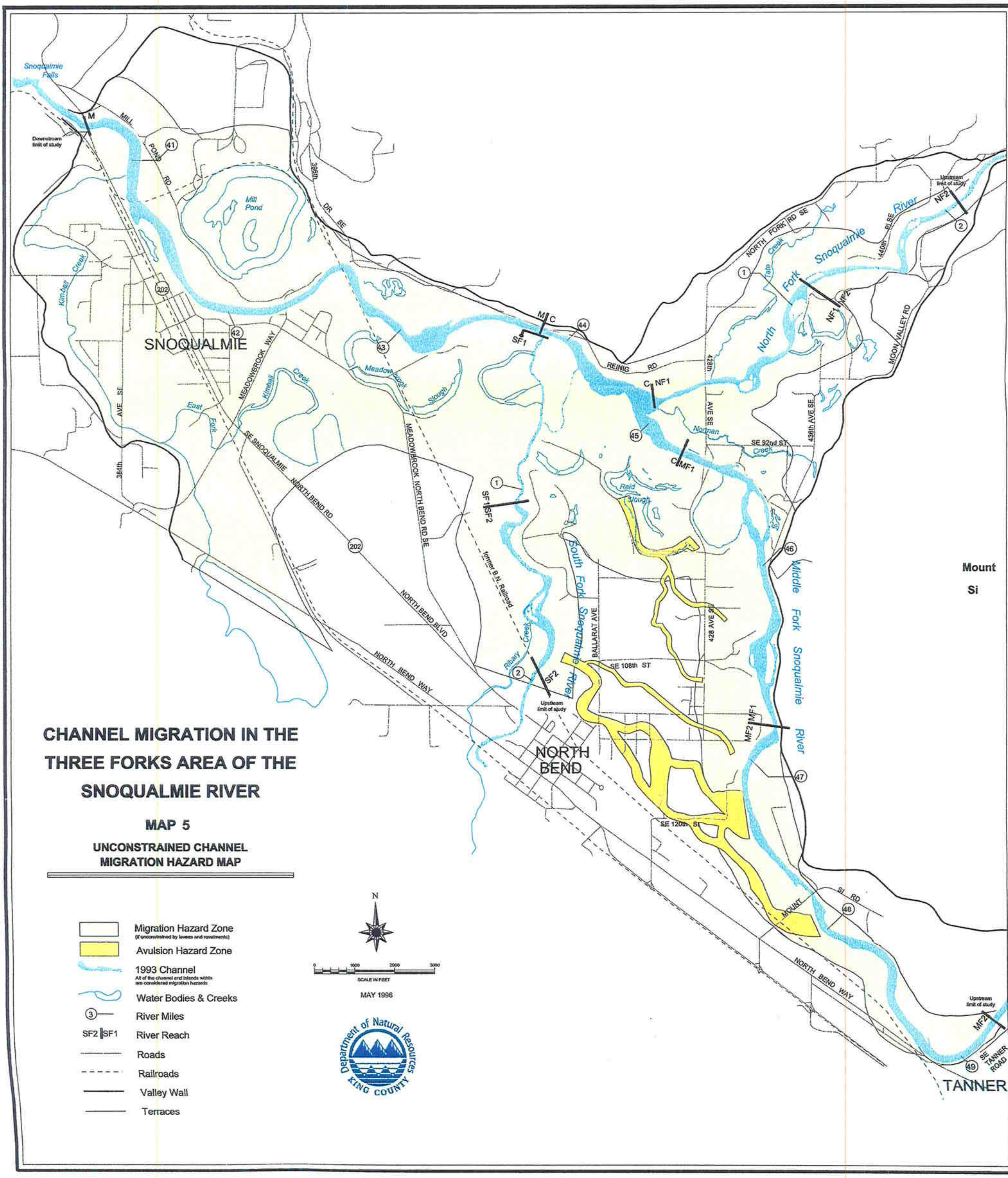
FLOODPLAIN CHANNELS

FLOODPLAIN CHANNELS

- Cross-Floodplain Channels & Water Bodies
- Parallel Channels & Water Bodies
- 1993 Channel
- 3 River Miles
- SF2 | SF1 River Reach
- Roads
- Railroads
- Valley Wall
- Terraces

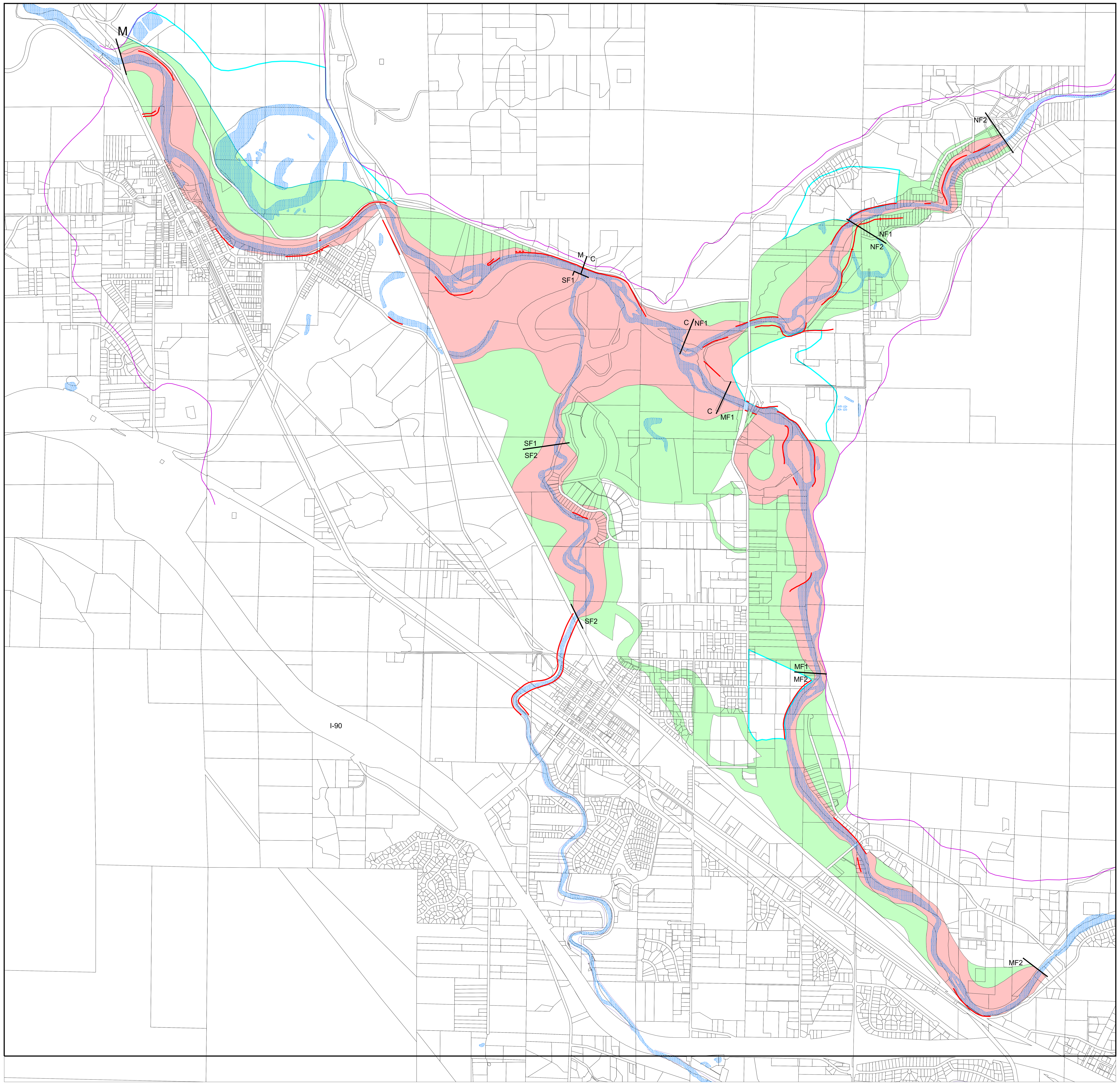
Notes

1. Floodplain channels east of the South Fork Snoqualmie River were digitized from 1993 and 1995 topographic maps by David C. Smith & Associates Inc. for King County SWM.
2. Floodplain channels west of the South Fork Snoqualmie River were digitized from 1961 topographic maps by King County.
3. All floodplain channels are shown as a single line, regardless of width.

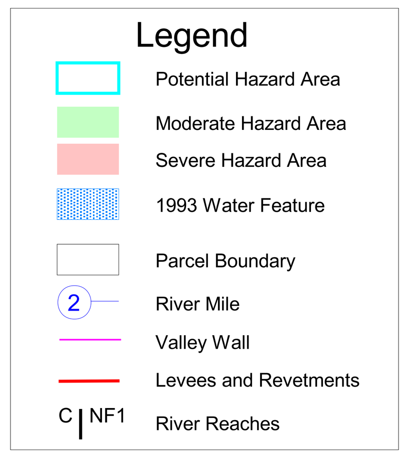

CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER
MAP 5
UNCONSTRAINED CHANNEL MIGRATION HAZARD MAP
Migration Hazard Zone
(if unconstrained by levees and revetments)
Avulsion Hazard Zone
1993 Channel
All of the channel and islands within are considered migration hazards
Water Bodies & Creeks
River Miles
River Reach
Roads
Railroads
Valley Wall
Terraces
N
SCALE IN FEET
MAY 1996
Department of Natural Resources
KING COUNTY
Snoqualmie Falls
Downstream limit of study
SNOQUALMIE
Mill Pond
MILL POND RD
Kimball Creek
East Fork
Meadowbrook Slough
MEADOWBROOK WAY
SE SNOQUALMIE NORTH BEND RD
MEADOWBROOK NORTH BEND RD SE
former B.N. Railroad
NORTH BEND BLVD
NORTH BEND WAY
Ribary Creek
South Fork Snoqualmie River
BALLARAT AVE
SE 108th ST
Upstream limit of study
NORTH BEND
Reinig RD
Raid Slough
Norman Creek
SE 92nd ST
428th AVE SE
436th AVE SE
Middle Fork Snoqualmie River
North Fork Snoqualmie River
Tate Creek
NORTH FORK RD SE
MOON VALLEY RD
Mount Si
MOUNT SI RD
SE TANNER ROAD
TANNER

CHANNEL MIGRATION IN THE THREE FORKS AREA OF THE SNOQUALMIE RIVER

In June 1999, the final map (labeled Sheet 6: Mitigated Channel Migration Hazard Map) of this 1996 channel migration study was adopted via the King County Channel Migration Public Rule for use by King County in regulating land use in the mapped channel migration hazard areas along the three forks of the Snoqualmie River. Sheet 6 of the original study has been replaced in this digital file by the adopted Snoqualmie River Channel Migration Area map, on the following page.



Snoqualmie River Channel Migration Area Map



Notes:

1. This hazard map was adapted from the Channel Migration in the Three-Forks Area of the Snoqualmie River Study, dated January 1996. The map was updated in April 1999 to include revisions made during preparations of the Channel Migration Public Rule. King County may make revisions to this map based on new information or changing channel conditions.

2. King County makes no assurances regarding ongoing or continuing maintenance or repair of public levees or revetments should flood events or other natural disasters significantly damage them.

3. Some inaccuracies may exist due to mapping and printing limitations.